Fluctuations of the West Greenland Ice Sheet, independent ice caps and mountain glaciers during the twentieth century

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Declaration of copyright

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Abstract

The Greenland Ice Sheet contains enough water to raise global sea levels by ~7 metres, but predictions of the actual potential future contribution in a warming climate vary widely. These can be improved through a better understanding of how the whole ice sheet and its outlet glaciers have responded to past and present climate fluctuations. Recent studies have observed that Greenland Ice Sheet outlet glaciers have been retreating and thinning at increasingly faster rates since the 1990s. However, few studies have investigated the behaviour of the numerous independent ice caps that surround the ice sheet, or the land-terminating outlet glaciers. In addition, recent retreat is rarely put into context with long-term twentieth century fluctuations. This study has mapped ice sheet outlet glaciers and margins, independent ice cap outlets and mountain/valley glaciers at 11 time steps between the Little Ice Age and 2009 in northwest and southwest Greenland. Length changes of different glacier classes and terminus environments are examined, and overall glacier fluctuations compared to regional air temperatures and precipitation. Glaciers in the northwest have retreated further than those in the southwest at most time periods, with the exception of 1943/53-1964 when southwest glaciers underwent their most rapid rate of retreat. Length changes in both regions are driven by air temperature and precipitation changes. Tidewater outlet glaciers have generally retreated shorter distances than land-terminating glaciers in both absolute and relative terms over long time periods. These results imply that recent rapid retreat of many tidewater outlet glaciers in Greenland is not unprecedented, and may represent natural cyclical fluctuations rather than a long-term shift in behaviour. Ice sheet outlet glaciers have retreated shorter relative distances than independent ice caps and mountain/valley glaciers. Ice sheet margins advanced in the southwest between 1964 and 2001, and a slight advance of many independent glaciers was observed from ~1964-1987. It is unclear why this advance occurred. This study highlights the need for more research into the fluctuations of the independent ice caps and land-terminating glaciers in all regions of Greenland. In addition, more detailed research into the response of glaciers of all classes and terminus environments to climate change during the whole of the twentieth century is required to put recent changes into context.

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Chapter 1

Introduction

1.1 Introduction

In the light of increasing evidence for global climate warming, determining the past and present fluctuations of the Greenland and Antarctic ice sheets plays a vital role in predicting future mass loss and sea level rise (IPCC, 2007), as the Greenland Ice Sheet alone contains enough fresh water to raise sea levels by ~7 m (Church and White, 2006). Recent monitoring of the largest Greenland Ice Sheet outlet glaciers indicates that many have retreated rapidly since the 1990s (Rignot and Kanagaratnam, 2006; Moon and Joughin, 2008; Box, 2009), and this behaviour has been attributed to atmospheric and ocean warming (Price, 2009; Thomas *et al.*, 2009). Furthermore, extensive thinning and an acceleration in mass loss at the ice sheet margins has been generally observed, accompanied by an increase in flow speed in many regions (Pritchard *et al.*, 2009; Joughin *et al.*, 2010). Mass loss from the Greenland Ice Sheet increased from ~137 Gt a^{-1} to ~ 286 Gt a^{-1} between 2002 and 2009 (Velicogna, 2009), and this is estimated to be equivalent to between 1.7 and 3.8 mm total sea level rise since 2003 (Bromwich and Nicolas, 2010; Wu *et al.*, 2010).

The majority of the research into fluctuations of the Greenland Ice Sheet during the twentieth century has been focussed on the marine-terminating (tidewater) outlet glaciers; in particular Jakobshavn Isbrae, Helheim and Kangerdlugssuaq, which between them drain ~40% of the ice sheet (Bell, 2008; Howat *et al.*, 2008; Joughin *et al.*, 2008, Nick *et al.*, 2009). Previous studies have shown, however, that whilst tidewater glaciers respond rapidly to climatic changes the nature and duration of this response is controlled by confounding factors such as fjord topography and water depth, making them unreliable indicators of overall ice sheet response to global warming (Warren, 1991; Weidick, 1994; Moon and Joughin, 2008). Despite this, research into the fluctuations of the many land terminating outlet glaciers and sections of ice sheet margin has been very limited, particularly in recent decades.

In addition, few researchers have investigated the fluctuations of the many independent ice caps and mountain glaciers found around the coast of Greenland, yet these cover an area of ~48,600 km^2, and comprise ~5% of global mountain glacier coverage (Weidick and Morris, 1998). With the rise in temperature predicted to be greatest in the polar regions (IPCC, 2007) melting of these ice caps could result in a small but significant rise in sea level (Dyurgerov and Meier, 2005). Previous work in Greenland suggests that independent glaciers are very sensitive to climate changes, and have retreated significantly during the twentieth century (Gordon, 1981; Weidick *et al.,* 1992, Yde and Knudsen, 2007). However, detailed studies of independent glacier fluctuations for the whole of the twentieth century have thus far only been undertaken on glaciers in Disko Bugt in Central West Greenland (Yde and Knudsen, 2007; Citterio *et al.*, 2009).

1.2 Thesis aims

1.2.1 Aims

As described above, the majority of recent research into glacier behaviour in Greenland has focussed on the fluctuations of the large tidewater outlets of the main ice sheet during the past two decades, up-to-date information on the fluctuations of land glaciers and the independent ice caps and mountain glaciers is limited, and few studies have examined the recent rapid retreat of tidewater outlet glaciers in Greenland within the context of long-term twentieth century length changes. In order to address these deficiencies, the following project aim was developed:

- To examine and compare the fluctuations of the ice sheet margin, ice sheet outlet glaciers, independent ice caps and mountain/valley glaciers in two regions of West Greenland during the twentieth century, with relation to climatic and non-climatic controls.

1.2.2 Objectives

This aim has been broken down into the following specific objectives:

- To map changes in terminus positions of ice sheet margins, ice sheet outlet glaciers, independent ice cap outlet glaciers and mountain/valley glaciers since the Little Ice Age.
- To compare the relative rates of advance/retreat of different glacier classes.
- To examine the influence of terminus environment on glacier behaviour, with a particular focus on comparing tidewater to land-terminating glaciers.

- To compare glacier behaviour in the north and south during the 20th century.
- To assess the links between glacier changes and regional air temperature and precipitation trends.
- To compare the data on glacier length changes presented in this study to that published in previous studies.

1.3 Study areas

Greenland is the largest island in the world covering an area of ~ 2.17 million km^2, approximately 82% of which is covered by the main ice sheet and 7% by local ice caps and glaciers (Weidick, 1995). Greenland has a latitudinal extent of ~2500 km, with all but the southern tip within the Arctic Circle. In consequence there are big contrasts in climate between the north and south, with both temperature and precipitation decreasing with increasing latitude (Weidick, 1995; Box, 2002). Longitudinal differences in climate have also been observed, with the east and west coasts typically experiencing opposite temperature trends (Box, 2002).

Ocean temperatures around Greenland are controlled by variations in the three main currents: the West Greenland Current, East Greenland Current and Irminger Current (Buch, 2000; see Figure 1.1). The East Greenland Current flows southwards along the east coast, and chiefly comprises very cold polar water from the Arctic Circle. The Irminger Current is a warm, saline water mass derived from the Gulf Stream and North Atlantic Current that flows northward to the Denmark Strait, then turns and flows southward down the east coast. When these currents reach Cape Farewell at the southern tip of Greenland they divide, and part of each rounds the cape to form the dominant components of the West Greenland Current. The East Greenland Current is found closest to the shore, and only extends as far northwards as Nuuk, whilst the Irminger Current flows to the west and below the East Greenland Current and reaches as far north as Thule (Buch, 2002). Variations in both ocean temperatures and atmospheric conditions in Greenland are predominantly controlled by variations in the North Atlantic Oscillation (NAO) (Buch, 2002; Ribergaard *et al.*, 2008). During a positive NAO, Greenland is cooler and drier and both the Irminger and East Greenland currents are weaker, and vice versa during a negative NAO (Buch, 2002).

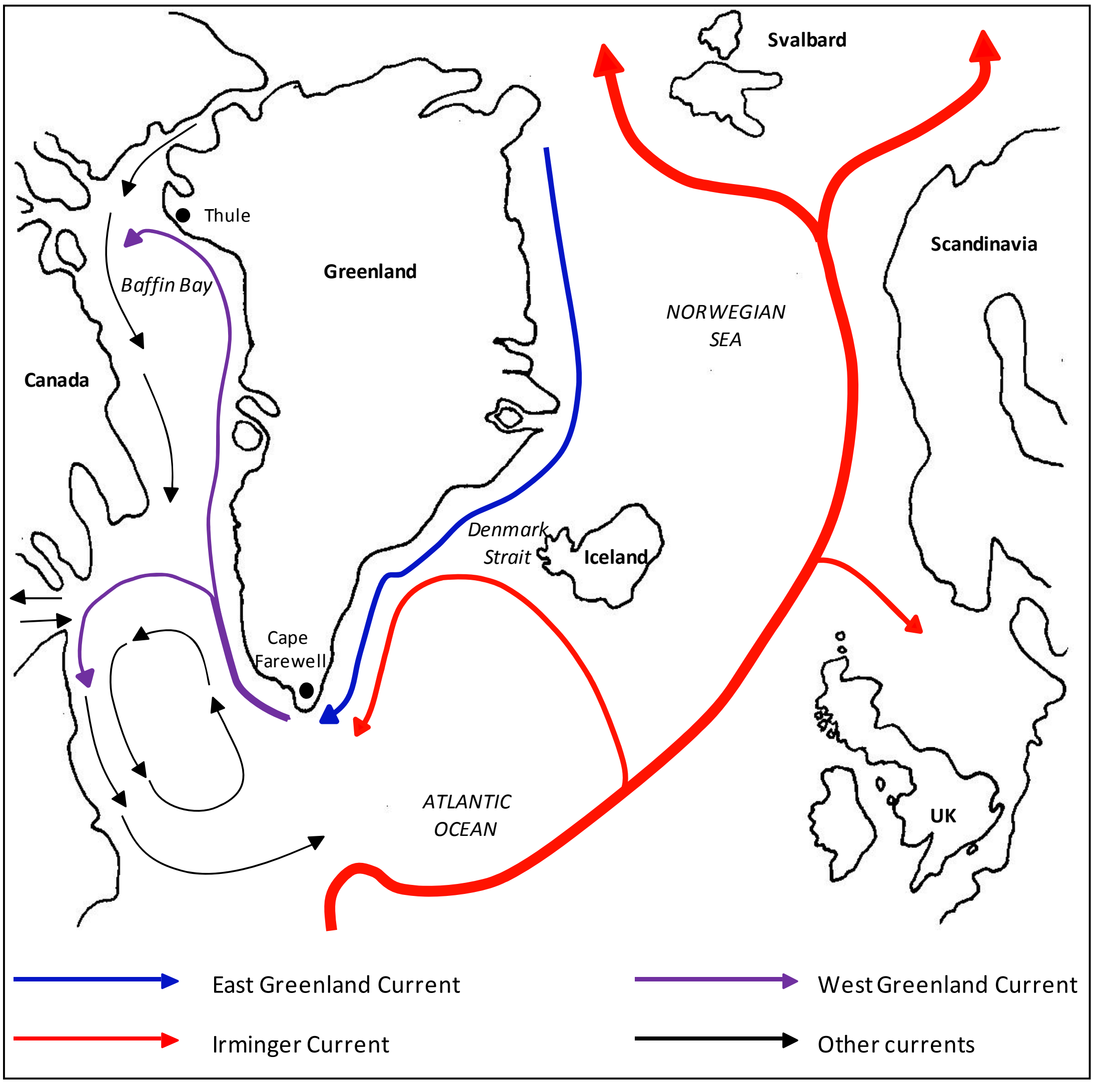


Figure 1.1: Map showing the major ocean surface currents around Greenland.

The two study areas chosen for this research are in the northwest and southwest of Greenland, centred around the North Ice Cap and Sukkertoppen Ice Cap respectively (Figure 1.2). It was decided to select two regions of a similar longitude along the West Greenland coast so that differences in glacier behaviour between the north and south could be examined. These particular regions were chosen as they each have several independent ice caps and numerous mountain glaciers, none of which have been studied in any great detail in recent decades. In addition, long-term data records on air temperature and precipitation are available for both regions, dating back to the 1950s in the northwest and 1880s in the southwest. More detailed descriptions of each study area are given in the following sections.

1.3.1 Northwest

The northwest region covers an area of approx 52,500 km^2 between 76-78° north and 64-73° west. The ice sheet margin is very close to the coast here, with numerous outlet glaciers, predominantly tidewater, draining into Smith Sound and the northernmost part of Baffin Bay (Blake, 1999). To the north is Inglefield Land, a large, ice free plateau bounded by the main ice sheet, which is notable for the almost complete absence of outlet glaciers (Davies and Krinsley, 1962). The northwest has several independent ice caps, of various sizes, located on high plateaus. The largest of these is the North Ice Cap, which sits on a peninsula in the centre of the bay, and covers an area approximately 2100 km^2 (Kelly and Lowell, 2009). The ice cap is made up of a number of large ice domes and is confluent with the main ice sheet at its westermost edge, where it forms a prominent ice cliff known as 'Red Rock', which has been the focus of many detailed studies (e.g. Goldthwait, 1960, 1961, 1971). Long stretches of vertical ice cliffs and steep ramps are widespread throughout the northwest study area, and are formed when the lower layers are frozen to the bedrock and the upper layers then slowly advance over them (Weidick, 1995). Surge-type behaviour has only been observed for one glacier, Harald Moltke Brae (Weidick, 1995), but it is possible that other glaciers in the study area may also demonstrate surge behaviour. Northwest Greenland has a very arid climate, with an annual mean temperature of -12°C (Weidick, 1995) and 65 mm of precipitation (Davies and Krinsley, 1962) measured at Thule Air Base (shown in Figure 1.2).

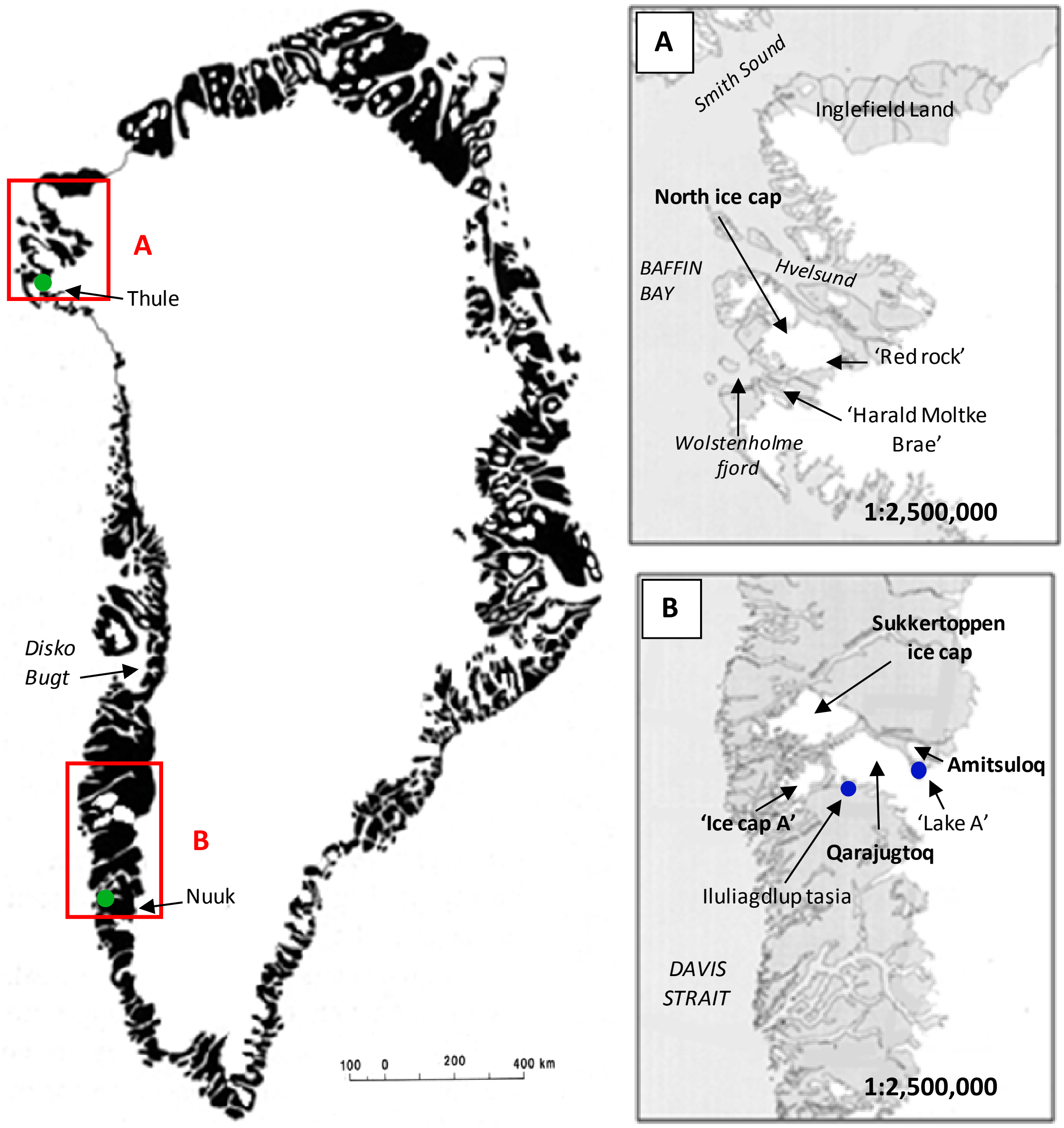


Figure 1.2: Location map showing the location of the northwest (A) and southwest (B) study areas. The green dots mark the location of two of the primary meteorological stations, and the blue dots mark two ice-dammed lakes.

1.3.2 Southwest

The southwest study area covers an area of approximately 119,600 km^2 between 63-67° north and 49-54° south. A wide strip of predominantly ice-free land separates the ice sheet from the ocean, characterised by mountainous Alpine topography at the coast and low hills towards the ice sheet (Haynes, 1972). The four independent ice caps in this area are Qarajugtoq (~2010 km^2), Sukkertoppen ice cap (~1983 km^2), Amitsuloq and an unnamed ice cap 'A', which are surrounded by numerous individual cirque and valley glaciers (Figure 1.2). These ice caps sit on a high plateau and drain radially into the many fjords and troughs that dissect this stretch of coastline (Haynes, 1972). Glacier fluctuations in west Greenland have been more extensively studied and observed than in any other region, with records for some individual outlets dating back 150 years. No surging glaciers have been reported in this region of Greenland, although several have been reported further up the coast in Disko Bay (Weidick, 1995).

The area does have two of the largest ice-dammed lakes in west Greenland, Iluliagdlup tasia and un-named 'lake A' (Figure 1.2). Little is known about the latter lake, but Iluliagdlup tasia is reported to drain catastrophically under the outlet glacier at its western end at 6 - 11 year intervals (Weidick, 1995). The climate of this region varies with distance from the coast, with high levels of precipitation and a maritime climate grading into a drier, continental climate towards the ice sheet (Haynes, 1972). Precipitation also decreases from south to north along the western coast (Weidick, 1995). Long-term records of air temperature and precipitation have been made since 1873 at Nuuk, which is located near the coast at the southern end of the study area (Figure 1.2).

Chapter 2

A review of global and Greenland glacier fluctuations

2.1 Introduction

The behaviour of both the Greenland Ice Sheet and mountain glaciers worldwide have been extensively researched during the past century. The study of glacier fluctuations can provide useful information on past climate changes (Oerlemans, 2005), and the significant increase in global temperatures predicted for the next 100 years has led to increasing interest in future glacier contributions to sea level rise (IPCC, 2007). For this to be modelled accurately, information on the response of glaciers to past climatic changes is required. Whilst much progress has been made in determining how glaciers have fluctuated during the twentieth century, and what factors may drive and influence these changes, further research into both areas is still needed (Owen *et al.*, 2009).

The aim of this chapter is to put the current study into context, by reviewing previously published literature on glacier fluctuations since the Little Ice Age (LIA). Firstly, the current understanding of global trends in ice cap and mountain glacier changes during the twentieth century is briefly summarised (Section 2.2). A detailed review of previous research into the behaviour of the Greenland Ice Sheet is then given in Section 2.3, followed by a review of work focussing on the independent ice caps and mountain glaciers that surround the main ice sheet (Section 2.4). Finally, a brief summary of twentieth century climate trends in Greenland is presented in Section 2.5.

2.2 Global trends in glacier behaviour during the twentieth century

Written records of some mountain glacier fluctuations extend back as far as 1600 A.D. (Oerlemans, 2005). However, collation of glacier change information from around the world did not begin until 1894, when the International Glacier Commission (IGC) was set up. Despite various organisational changes, quantitative and qualitative data of global glacier length changes have been published regularly ever since (Haeberli, 1998). Efforts to collate all the data began with the creation of World Glacier Inventory (WGI) by the World Glacier Monitoring Service (WGMS; a follow-on from the IGC), in 1985. The inventory records changes in glacier characteristics, such as length, mass balance, area, volume and thickness, over time. Following on from the WGI, a project designed to monitor the world's glaciers using satellite imagery has recently been launched. The Global Land Ice Measurements from Space (GLIMS) database collates imagery and information on glacier change from numerous research institutes around the world. In addition, the project aims to develop software programs to aid glacier mapping, terrain classification and change analysis. In the future, it is hoped that this database will allow us to gain a better understanding of the causes of glacier change, their hazardous effects on communities and the potential future impacts of climate change on both (Kargel *et al.*, 2005; GLIMS, 2008).

A comprehensive survey of data on global glacier mass balance and length was published as part of the most recent report by the Intergovernmental Panel on Climate Change (IPCC, 2007). The report highlights the importance of studying mountain glacier fluctuations, as they provide one of the most visible indications of the effects of climate change, and represent a maximum potential sea level rise of between 0.5 ± 0.1 and 0.72 ± 0.2 metres (this estimate includes glaciers surrounding the Greenland and Antarctic Ice Sheets; IPCC, 2007). Global temperatures are predicted to rise by between 1.8 and 4°C by the end of the twenty-first century, and knowledge of past glacier fluctuations will be vital for predicting the glacier retreat and sea level rise that might result (IPCC, 2007).

The major limiting factor for any study of global trends in glacier behaviour is that the dataset is heavily biased towards the European Alps, Scandinavia and Iceland, with few measurements available for glaciers in the rest of the world prior to the 1970s (Oerlemans, 2005). In addition, most research has focussed on glacier change in the northern hemisphere, so records for southern hemisphere change are particularly sparse (Meier, 1984). These issues make it hard to accurately assess global changes in ice caps and mountain glaciers during the twentieth century. The following four sub-sections of this review first summarise our current understanding of twentieth century fluctuations of mean global glacier length (2.2.1) and mass balance (2.2.2). Twentieth century behaviour of Arctic glaciers is then briefly reviewed in Section 2.2.3, and a summary given in Section 2.2.4.

2.2.1 Global fluctuations in ice cap and mountain glacier lengths

The majority of research into ice cap and mountain glacier length changes during the twentieth century has been carried out on specific regions, with less focus on explicit assessment of global patterns. An exception to this is a study by Oerlemans (2005), who used records for 169 glaciers to calculate regional mean retreat rates from 1700-2000. When smoothed, the data indicate that glaciers worldwide advanced overall from 1700-1800, after which a general retreat began (see Figure 2.1). The amount of retreat per year increased steadily until 1970, when annual retreat rates remained fairly steady for 20 years. In 1990, glaciers once again began retreating greater distances every year. Only a small handful of glaciers advanced between 1800 and 2000, and Oerlemans (2005) suggests that these were probably influenced by high local levels of precipitation. Although 93 of the glaciers studied were located in the European Alps, a comparison of Alp and non-Alp glacier length changes showed a close agreement in trend (Figure 2.1). This supports the idea that length changes at the century scale have occurred uniformly across the globe (Oerlemans, 2005).

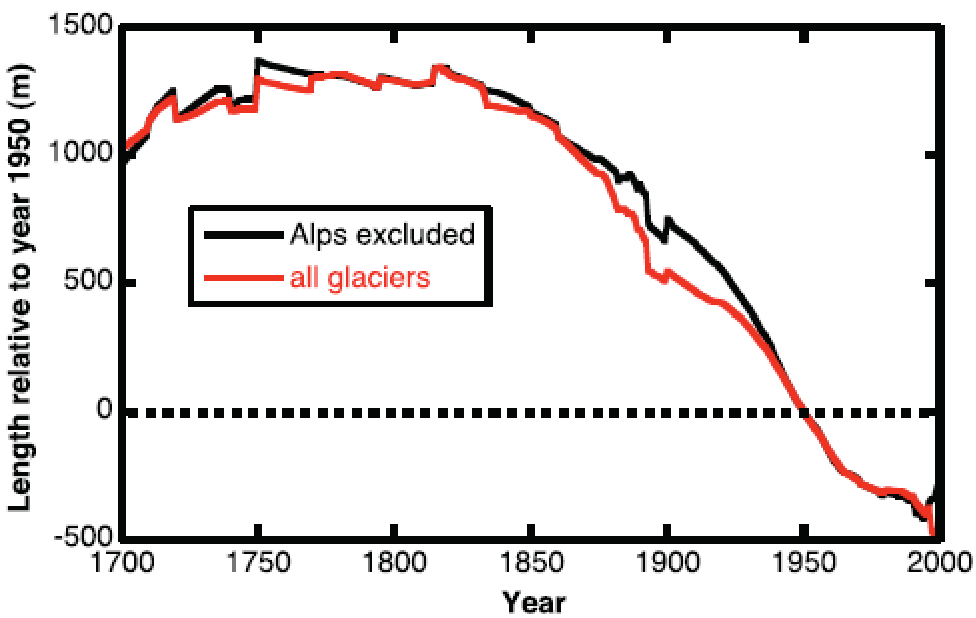


Figure 2.1: Smoothed regional mean length variations of 169 glacier termini worldwide from 1700-2000, showing length changes relative to terminus positions in 1950 (*from* Oerlemans, 2005:676).

A more detailed review of 30,420 length change observations held by the WGI has recently been published (WGMS, 2008a). The analysis supports the observation of a general glacier recession worldwide between the late 19th century and present day.

The data also suggest that glaciers retreated the greatest distances during the 1920s and 1940s, with a period of minimal retreat and some advance during the 1970s, followed by a sharp increase in mean amounts of retreat per year during the 1980s (WGMS, 2008a). Whilst the results support Oerlemans' (2005) observations, they also demonstrate significant deviations from the global trend in different regions over shorter time periods. The authors suggest that this may be partly the result of differences in individual glacier size, class (e.g. cirque or valley) and terminus environment. This highlights the important role that choice of study area can play in influencing analysis of glacier change at shorter timescales (WGMS, 2008a).

Glaciers surrounding the Greenland and Antarctic Ice Sheets are usually excluded from global analyses of mountain glacier length and mass balance changes (Hock *et al*., 2009), despite their making up ~16% of global glacier coverage (Barry, 2006). A detailed review of independent glaciers in Greenland is given in Section 2.4. Studies of Antarctic Ice Sheet independent glaciers are few and far between, and have generally focussed on change around the Antarctic Peninsula. Recent research by Rau *et al*. (2004) and Cook *et al*., (2005) reveals that glaciers in this region retreated overall from 1986-2002 and 1940-2001, respectively. Both studies also highlight the varying behaviour displayed by glaciers in different locations and environments within this region. Rau *et al.* (2004) explain this behaviour as a direct consequence of variations in regional climate. Cook *et al.* (2005) extend this point to suggest that the pattern of significant retreat began at the northern tip of the Peninsula, and has migrated southwards over time as the climate warms. Overall, 87 % of the 244 glaciers studied by Cook *et al.* (2005) show overall retreat during the study period. It is interesting to note that 29 out of the 32 glaciers that advanced or remained stable drain the main ice sheet. Only 3 mountain glaciers or independent ice cap outlets advanced. This supports the notion that glacier size and class can strongly influence individual responses to climate change. The contrast in distances retreated by land and tidewater terminating glaciers is also briefly discussed by Rau *et al*. (2004). They found that glaciers with floating tongues had retreated further than those that terminated on land.

2.2.2 Global fluctuations in mountain glacier mass balance

Long-term measurements of glacier mass balance are only available for the past 70 years at most (WGMS, 2008a). However, Meier (1984) developed a method for using recent seasonal mass balance measurements, combined with 25 long term records of glacier volume, to estimate global changes in mountain glacier volume between 1900 and 1960. The results suggest that total ice area decreased by 5-44 % in all 13 regions studied. More recently, Dyurgerov and Meier (1997a) used mass balance data for 200 mountain and ice cap outlet glaciers to examine global changes between 1946 and 1993. Their results indicate a reduction in global glacier area of between 6 x 10^3 and 8 x 10^3 km^2 between 1961 and 1990. Dyurgerov and Meier (1997b) suggest that this evidence supports the theory that changes in mass balance occur at a global scale, and do not vary significantly between regions. However, they also noted that whilst continental areas have experienced a steady decrease in glacier area and volume, the mass balance of maritime regions fluctuates annually. In addition, some parts of Europe exhibited a positive trend in mass balance (e.g. Iceland and Norway). It should be noted that this analysis does not cover mass balance changes during the past two decades.

Further investigation of global mass balance was undertake by Ohmura (2006), who used winter and summer data to examine global mass balance changes over the past half-century. The results support previous findings of a negative mass balance in almost all regions from the 1960s onwards, with the mean amount of mass lost per year increasing over time (Figure 2.2). This trend appeared to intensify from 1990-2000, with the mean rate of annual mass loss twice as high as that of the 1980s. Ohmura (2006) uses these figures to estimate that the overall contribution to sea level rise by mountain and ice cap outlet glaciers during the twentieth century was approximately 43 mm.

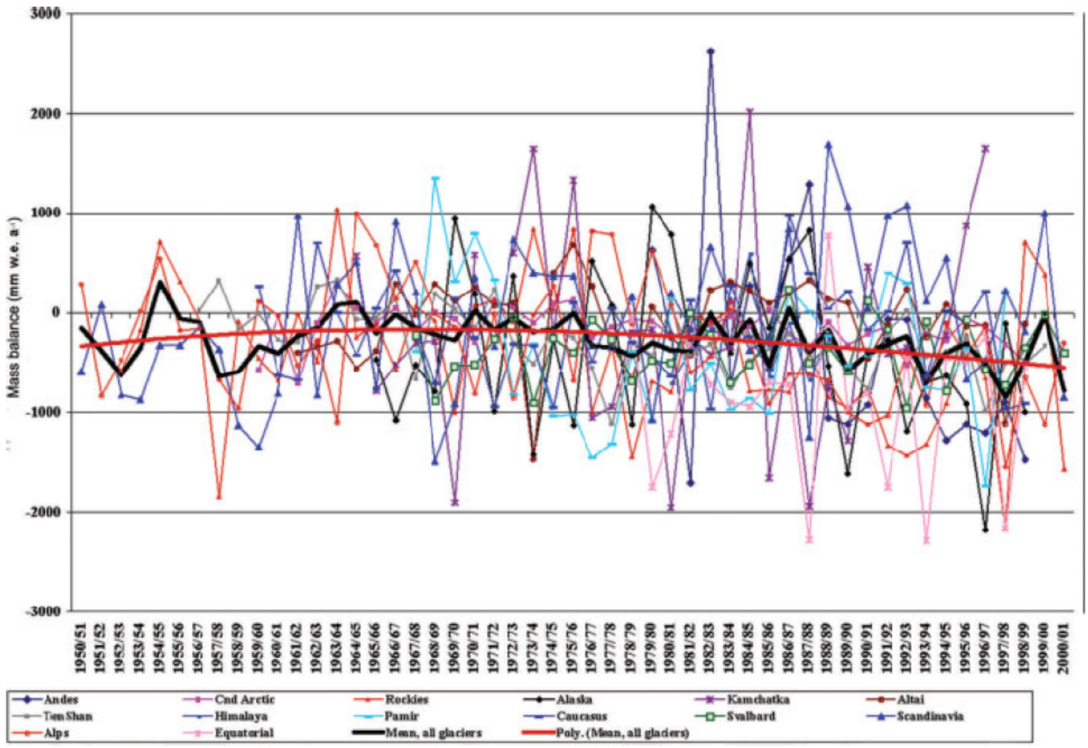


Figure 2.2: Annual mass balances of 14 regions around the world between 1950 and 2000, representing 68% of the total glaciated area outside of Greenland and Antarctica. The thick black line is an area-weighted global mean. Graph taken from Ohmura (2006: 362).

Calculations of cumulative global mass balance changes between 1946 and 2005 based on all available measurements held by the World Glacier Monitoring Service have recently been published (WGMS, 2008a; Zemp *et al*., 2009; see Figure 2.3). The data suggest an overall decrease in global mean specific mass balance of approximately -22 metres water equivalent (w.e.; WGMS, 2008a; Zemp *et al*., 2009) during this time period. With mean global ice thickness estimated to be between 100 and 180 m w.e. (WGMS, 2008a:29), this represents a significant mass loss. The results also reveal that glaciers lost mass rapidly between 1946 and 1956, followed by a period of slower reduction in size between 1956 and 1975. Annual amounts of ice loss increased sharply once more between 1975 and 1995, and have accelerated further since then (WGMS, 2008a; Zemp *et al*., 2009; see Figure 2.3).

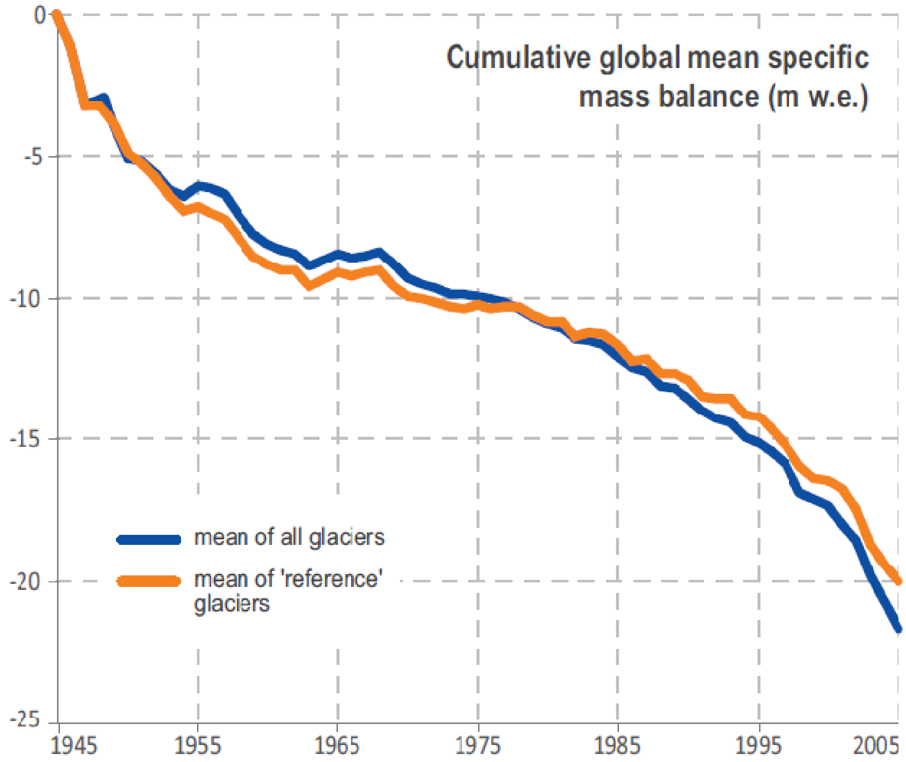


Figure 2.3: Cumulative global mean mass balance between 1945 and 2005 for all glaciers with measurements, and for 30 reference glaciers with long-term records (from WGMS, 2008: 30).

Estimates of global mass balance generally exclude those glaciers surrounding the Greenland and Antarctic Ice Sheets. Due to a lack of measurements, estimates of independent glacier mass balance for Antarctica have often been extrapolated from global or Arctic averages, with a more accurate long-term average having only recently been published by Hock *et al.* (2009). They used a previously published global hydrographic dataset to assess the area of individual glaciers around the Antarctic Ice Sheet, and create a grid-based model of estimated mass balance. The data indicate that overall ice loss occurred between 1961 and 2001, which contributed 0.22 ± 0.16 mm a^{-1} to sea level (28% of the total global mountain glacier contribution). The amount of mass loss varied between regions, with the majority occurring around the Antarctic Peninsula in the northwest, whilst East Antarctic glaciers remained fairly stable. Hock *et al.* (2009) highlight the important contribution that independent glaciers surrounding the ice sheets can make to sea level, and the need for more research into their past and present behaviour.

In a recent review of global mass balance estimates, Braithwaite (2009) suggest that glacier mass loss may have been overestimated, because the long-term data set is biased towards glaciers located in wetter conditions than the average for global glaciated areas. Glaciers in areas with high precipitation tend to undergo greater fluctuations in mass balance, and are likely to be more sensitive to changes in temperature and precipitation. Therefore, observed fluctuations, particularly for the 30 reference glaciers, are likely to be larger than the global average suggesting that future mountain glacier contribution to sea level rise has also been overestimated (Braithwaite, 2009).

Quantifying how long glaciers of different sizes take to respond to climate changes is important for predicting how they are likely to behave in the future. Johannesson *et al.* (1989) define glacier response time as the time taken for glacier geometry to adjust to climate. This is not the same as the time required for the terminus to respond (Bahr *et al.*, 1998). Response time (τ) can be estimated using the following simple equation:

$$\tau = \frac{H}{B} \qquad \textit{Equation 1}$$

where H is the ice thickness and B the mass balance rate at the terminus (Johannesson *et al.,* 1989; Bahr *et al.,* 1998; Raper and Braithwaite, 2009). In essence, this states that larger glaciers respond more slowly to climate changes than smaller glaciers (Bahr *et al.*, 1998). Paterson (1994) used this equation to estimate the response times of temperate marine glaciers (15-60 years), ice caps in Arctic Canada (250-1000) and the Greenland Ice Sheet (3000 years). Raper and Braithwaite (2009) later used a refined version of Equation 1 to demonstrate that glaciers in warm, wet climates respond more rapidly to climate perturbations than those in cold, dry regions.

2.2.3 Trends in Arctic glacier fluctuations

For the purposes of this study, the Arctic region is defined as the area of the globe north of 60°, and includes Canada, Norway, Russia, Alaska, Iceland, Scandinavia and Greenland. Excluding the Greenland Ice Sheet, it has ~275,000 km^2 of ice caps and mountain glaciers (Dowdeswell *et al.*, 1997). Iceland and Svalbard have the largest number of long term length and mass balance records, with most regions having sparse data for the first half of the twentieth century (WGMS, 2008a). A study of glacier length changes throughout the whole Arctic region found that the majority of glaciers have retreated during the twentieth century, including those with both land and tidewater termini (Dowdeswell, 1995). This is supported by investigations of the 40 glaciers with long-term mass balance records, which found that almost all of these glaciers have lost mass since the 1940s, although there are significant regional variations in timing and amount of loss (WGMS, 2008a). An investigation of change in mass by latitude found that whilst the majority of glaciers measured in the High Arctic (>70°) lost mass, half of those measured in the Low Arctic (60-70°) gained mass overall (Dowdeswell *et al.*, 1997). These glaciers are mostly located in Iceland and Svalbard (WGMS, 2008a).

These studies do not include data on mass balance changes for the past twenty years, but a more recent review by Braithwaite (2009) indicates a growing tendency towards negative mass balance since the late 1990s (Figure 2.4). In addition, those few glaciers that have grown during this period have much smaller positive mass balances than in previous years. A comparison of the data for Arctic glaciers to global mass balance reveals that they have undergone more muted variations (Braithwaite, 2009).

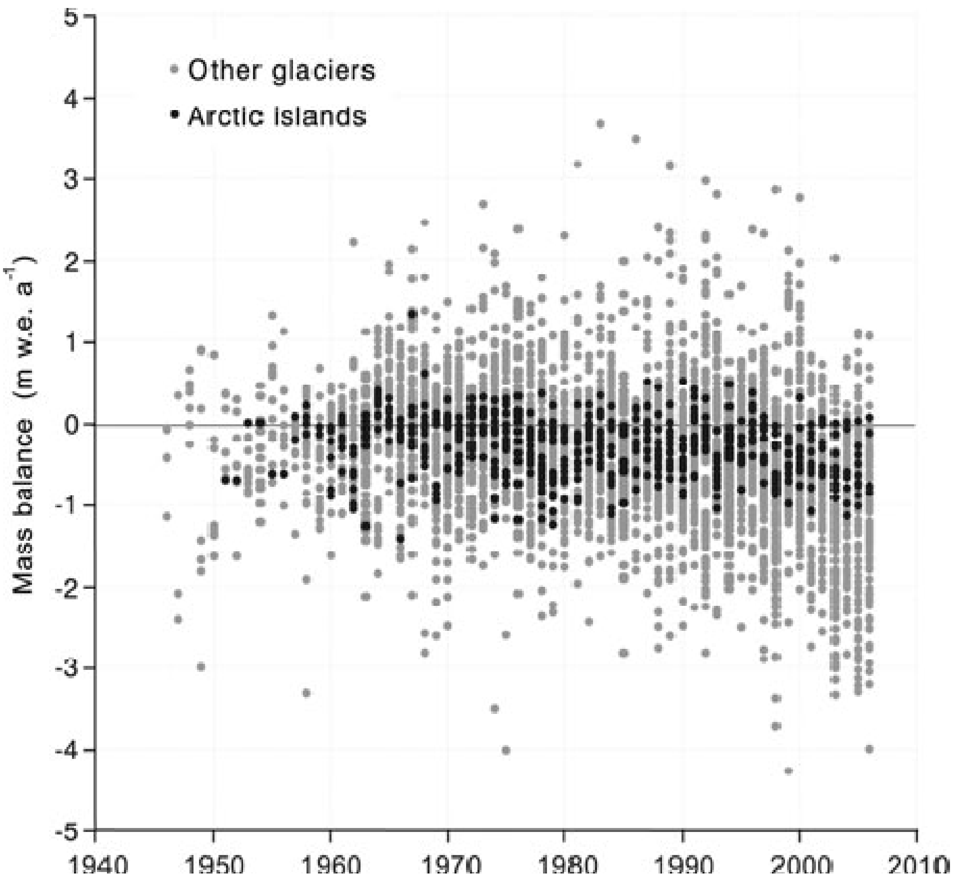


Figure 2.4: A comparison of Arctic glacier (black dots) and global (grey dots) mass balance measurements for each year between 1946 and 2007, using all available data (from Braithwaite, 2009: 193).

2.2.4 Summary of global glacier fluctuations during the twentieth century

Research suggests that glaciers worldwide have decreased in both length and mass during the twentieth century, although not at a constant rate. In general, rates of glacier retreat appear to have been highest during the 1920s, 1940s and 1980s onwards, with a possible acceleration in retreat observed for the 1990s and 2000s. In contrast, the period from 1950-1970 appears to have been characterised by low rates of retreat. Research into the fluctuations of independent glaciers surrounding the Antarctic Ice Sheet indicates that significant retreat has occurred during the second half of the twentieth century, although not in all regions. Patterns of retreat may not necessarily mirror those of the main ice sheet. Research into glacier change in the Arctic regions indicates that overall retreat has occurred since the 1940s, although glaciers in some regions (most notably Iceland and Svalbard) had positive mass balances between the 1960s and 1990s.

2.3 Greenland Ice Sheet behaviour since the Little Ice Age

The Greenland Ice Sheet is the second largest glacier on Earth and covers approximately 80% of Greenland, or 1,736,095 km^2 (Weidick, 1995). The total ice volume is estimated to be 2,600,000 km^3 (Weidick, 1995), which amounts to ~9% of present global glacier ice volume (Weidick *et al*., 1992). This is equivalent to a sea level rise of ~7 m (Church and White, 2006). The aim of this section is to review published literature on the fluctuations of Greenland Ice Sheet outlet glaciers and mass balance of the ice sheet since the Little Ice Age. In the following sub-sections, ice sheet outlet glacier behaviour is first reviewed, in sections focussing on the findings of early (2.3.1) and late (2.3.2) twentieth century, and twenty-first century (2.3.3) regional studies, followed by a brief summary of papers that have examined trends around the whole ice sheet (2.3.4). Twentieth century variations in ice sheet mass balance are then examined (2.3.5), followed by a summary of research into recent mass balance, velocity and surface elevation changes (2.3.6). A summary of the key points is given in Section 2.3.7.

2.3.1 Early twentieth century regional studies of Greenland ice sheet fluctuations

The earliest information about the Greenland Ice Sheet comes from the accounts of the Vikings who settled there c.1000-1300 A.D., and from more recent historical documents of the settlers who arrived from c.1720 onwards (Weidick, 1959). However, these reports generally consist of imprecise or very brief descriptions of glacier positions, so are of limited value. The first scientific studies of the Greenland Ice Sheet were carried out during the late nineteenth century, and were principally descriptive in nature. Explorers including Rink (1853), Holm (1883), Chamberlin (1897) and Peary (1898) undertook expeditions to different regions of the ice cap, and produced reports containing photographs, sketch maps and descriptions of the main outlet glaciers. Interest in Greenland grew rapidly following these early investigations, and the beginning of the twentieth century saw several large expeditions set out to survey different regions of the ice sheet more accurately (e.g. Rasmussen, 1928; Koch, 1928;

Koch, 1940). Their reports contained much more detailed information on glacier characteristics and terminus positions.

As the twentieth century progressed, the focus of glacier research in Greenland expanded to include studies of past fluctuations, as well as current glacier dynamics. Much work in this field was undertaken by Anker Weidick, whose early papers combined historical maps, photographs, expedition reports and field work to give a better understanding of ice sheet outlet glacier fluctuations in south and west Greenland during the Holocene and historical time (c. 1600 A.D. onwards; Weidick, 1959, 1963, 1968). He concluded that glaciers in the Southwest and Southern West regions of Greenland retreated overall between 1850 and 1955 (see Figure 2.5 for ice sheet divisions). Retreat was slow between 1850 and 1890, and glaciers re-advanced to their probable maximum historical extent between 1890 and 1900 (Weidick 1959, 1963). This supposition is supported by later lichenomentric dating of some moraine limits in Southern and Central West Greenland, which also indicated that maximum historical extent occurred between 1890 and 1900 (Beschel and Weidick, 1973). After 1900, the majority of glaciers retreated slowly once more from 1900-1920, followed by a period of rapid retreat from 1920-1940, and subsequent steady retreat during the 1940s and 1950s (Weidick, 1959, 1963). Further investigation of glacier behaviour in the Southwest, Southern West and Central West regions (60-70°N) supported the view that overall retreat occurred during the late 19th and early 20th centuries, but also suggested that some glaciers showed signs of re-advancing during the 1950s (Weidick, 1968).

Weidick (1959) also noted that terminus environment is a strong influence on glacier behaviour. He observed that land glaciers had generally all retreated since 1900, whereas tidewater glaciers demonstrated a mixture of advance and retreat behaviour. When comparing the behaviour of the Greenland Ice Sheet to that of glaciers in other parts of the world, Weidick (1968) concluded that the timing of fluctuations was very similar. This paper was also one of the first to attempt to quantify the lag time between climate change and glacier response in Greenland; based on visual comparison of temperature data and terminus fluctuations, Weidick (1968) concluded that glaciers took up to 20 years to respond to climate forcing.

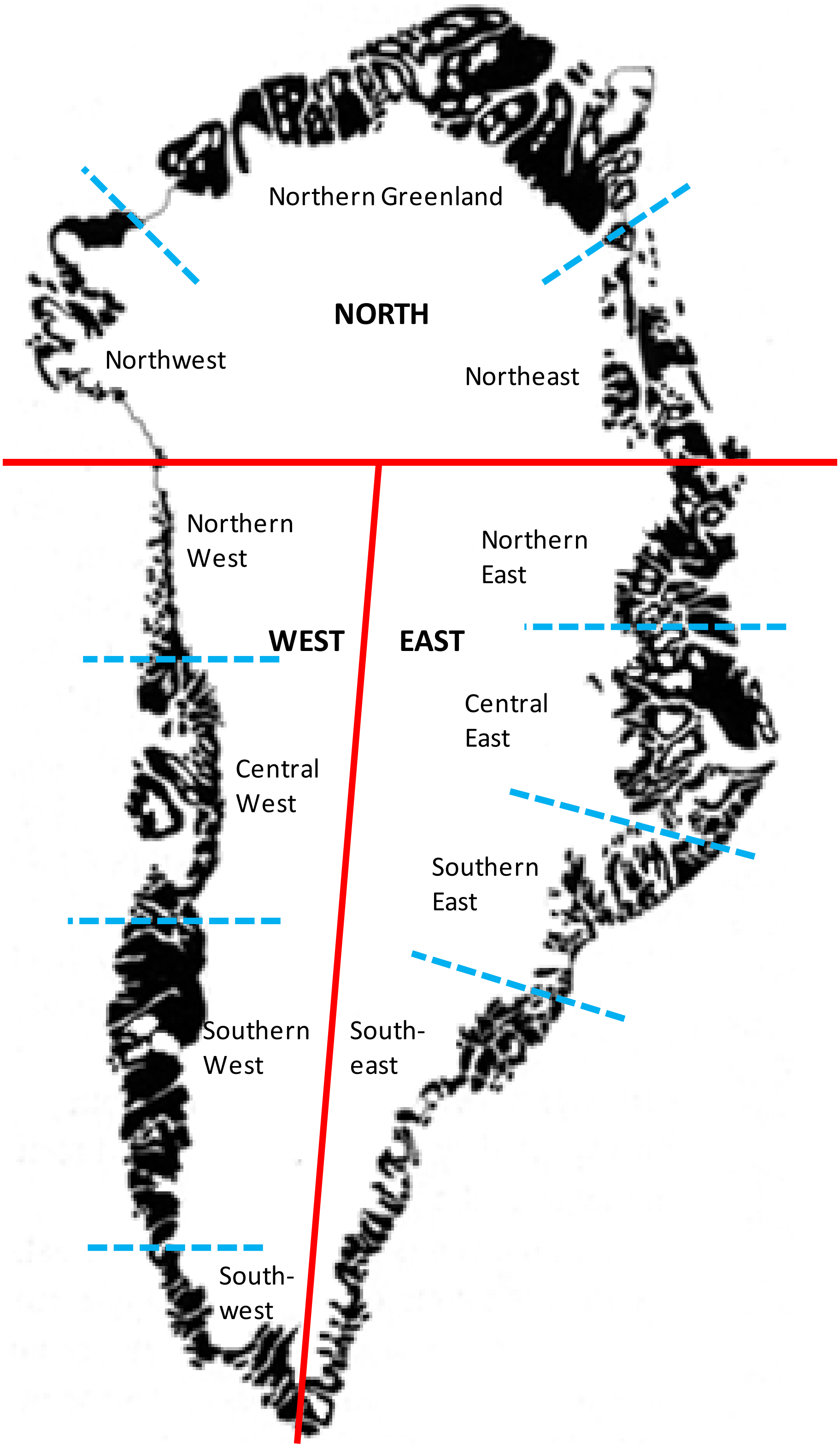


Figure 2.5: Map of Greenland showing the major hydrological basins, which are the basis for the subdivisions discussed in the text. The red lines distinguish the three main regions, based on flow data, and the blue dashed lines indicated hydrological boundaries (*after* Weidick, 1995: 5).

The link between climate change and glacier fluctuations became the main focus of research during the second half of the twentieth century, whilst the principal method of monitoring glacier change switched from field observations to satellite images. The first aerial photographs of Greenland were taken during the 1930s (Koch, 1945), and a database of images for different regions was slowly built up over the following few decades, until the first complete set of photographs was taken in 1987 (Weidick, 1995). A study by Davis and Krinsley (1962) was one of the first to use aerial photographs to investigate long-term fluctuations of Greenland glaciers in the context of climate change. This work focussed on glaciers in North Greenland and was, therefore, also the first major review of historical fluctuations in this region. Variations in the terminus positions of all major glaciers between 1900 and 1950 were mapped based on historical data, published observations and aerial photographs. By comparing these results to meteorological information for the region, the authors concluded that North Greenland glaciers had retreated overall between 1900 and 1950, and that this retreat appeared to correlate with a decline in precipitation. However, they also noted that many glaciers had very stable termini, particularly in the Northern Greenland sector, which they attributed to the stability of the cold, arid climate in this region.

2.3.2 Late twentieth century regional studies of Greenland ice sheet fluctuations

Historical data and aerial photographs continued to be used to investigate the long term fluctuations of Greenland Ice Sheet outlet glaciers throughout the twentieth century. Much of this research remained focussed on West Greenland. For example, Kollmeyer (1980) examined the behaviour of glaciers in the Central West, Northern West and Northwest coastal sectors (69-81°N) during the 1960s and 1970s, using photographs and surveys. The data indicated that the majority of glaciers in these regions had retreated during this time period, but that the amount of retreat observed generally decreased with increasing latitude. These findings are in contrast to those of a later study by Weidick (1994), who examined fluctuations of Southwest, Southern West, Central West and Northwest glaciers during the twentieth century. His results clearly indicate that the majority of glaciers in all regions were stationary or retreating during the first half of the century but had generally re-advanced since the 1950s, in many cases back to their LIA maximum positions. This discrepancy in observations may reflect a genuine difference in glacier behaviour between the northwest and southwest, or it could be explained by the characteristics of the glaciers examined in the respective studies. Whilst Kollmeyer (1980) focussed solely on tidewater glacier fluctuations, Weidick (1994) examined a mixture of land, tidewater and lake-terminating glaciers. Because glaciers with different terminus environments had previously been observed to respond differently to climate forcing (Weidick, 1959), this is one possible explanation for the different patterns of behaviour observed by the two authors. Some support for this theory is found when comparing Weidick's (1994) results to a study by Sohn *et al.* (1998). They examined the behaviour of 6 tidewater glaciers in West Greenland between 1962 and 1992, and reported that all of these outlets had retreated throughout this time period.

The role that terminus environment plays in modifying Greenland glacier response to climate change was confirmed by Warren (1991). He mapped the fluctuations of 72 glaciers in Southwest, Southern West and Central West Greenland (60°- 72°N) for the period 1943-1985 from aerial photographs and field observations, and compared them to regional meteorological data. The results clearly showed that whilst land and lake-terminating glaciers respond directly to climate forcing, tidewater glacier behaviour is also strongly influenced by local topography. As a consequence, tidewater glaciers often display opposite behaviour to land-terminating glaciers. These conclusions were supported by further work undertaken in southwest Greenland by Warren and Glasser (1992), who concluded that lake-terminating glaciers are the first to respond to climate change, followed by tidewater (although response is controlled by topography), and finally land-terminating glaciers. Lake-terminating glaciers have calving rates an order of magnitude lower than those of tidewater glaciers for any given water depth, due to the absence of tides and limited wave action. This makes them more stable, and coupled with the greater range of water temperatures probably explains how they can respond more quickly to climate than tidewater glaciers (Warren, 1991; Warren and Glasser, 1992). Land-terminating glaciers are the last to respond to climate because they have much lower mass exchange rates relative to calving glaciers (Warren and Glasser, 1992). This work highlights the importance of taking terminus environment into consideration when studying glacier fluctuations, and also the problems that can arise from relying on tidewater glacier fluctuations as an indicator of climate change.

Most of the research into the fluctuations of the Greenland Ice Sheet has focussed on outlet glaciers in the West and North regions, partly due to the lack of data for East Greenland. Despite this, some studies have used satellite data and aerial photographs to examine changes in East Greenland since the 1960s and 1970s. For example, Dwyer (1995) used Landsat imagery to quantify glacier change in Southern East Greenland since the 1970s. The results showed that some glaciers advanced and others retreated. Dwyer (1995) also noted that glaciers with the highest surface velocities were those with the largest drainage basins. More recently, Stearns *et al.* (2005) and Stearns and Hamilton (2006) used aerial photographs and satellite imagery to examine glacier fluctuations in Central East Greenland. They found that glaciers in the Scoresby Sund region have remained stable since the 1950s, although some have been observed to retreat overall. They suggest that this stability may be due to the relatively low air temperatures in this region (Stearns *et al.*, 2005).

2.3.3 Twenty-first century studies of Greenland ice sheet fluctuations

Research into Greenland Ice Sheet changes has been aided by the rapid development of sophisticated remote sensing techniques, which allow the whole ice sheet to be studied in greater detail. However, the majority of this technology has only been available since the 1990s or 2000s, so cannot be used to study long term trends. Demand for accurate predictions of how the Greenland Ice Sheet may respond to future climate change has increased in recent years, following predictions of a significant future increase in air temperatures (IPCC, 2007). This, coupled with the temporal limitations of the satellite data, has led to a shift in focus away from reconstructing twentieth century behaviour, towards modelling twenty-first century behaviour. Much research has been undertaken on Greenland's three largest glaciers (Jacobshavn Isbrae, Helheim and Kangerdlugssuaq), which between them drain ~40 % of the ice sheet (Bell, 2008). Ice front positions of these glaciers have been reconstructed using satellite imagery (e.g. MODIS and ASTER), and velocity measured by tracking surface features; the data indicate that Jacobshavn Isbrae began thinning and retreating rapidly after 1997, with Helheim and Kangerdlugssuaq following suit in 2000 (Joughin *et al.,* 2004; Holland *et al.*, 2008; Howat *et al.*, 2008; Joughin *et al.*, 2008). Examination of the fluctuations of other major Greenland tidewater outlets reveals a similar trend, with studies reporting widespread thinning and retreat of many glaciers around the whole of the ice sheet margin (Abdalati *et al.*, 2001; Moon and Joughin, 2008; Box, 2009; Thomas *et al.*, 2009). The southeast region has generally experienced the most rapid retreat (Abdalati, 2001; Moon and Joughin, 2008).

The rapid retreat and thinning of many tidewater ice sheet outlet glaciers exceeds that expected from changes in surface mass balance as a result of rising air temperatures, suggesting that changes in ice dynamics have led to dynamic thinning (Krabill *et al*., 2000; Sole *et al*., 2008; Holland *et al*., 2008), which occurs when glacier velocity exceeds that required for ice flux to balance accumulation (Sole *et al*., 2008). Zwally *et al*. (2002) suggest that warming air temperatures have led to surface melt occurring over wider areas and for longer periods. If more of this water is reaching the bed, it could result in faster ice flow as a result of increased basal lubrication. Modelling suggests that melt-induced sliding initially leads to ice front retreat, and consequent increase in mean ice thickness as the ablation area decreases. The steeper surface slope and increased ice thickness lead to higher basal shear stresses, which combined with increased basal lubrication by meltwater result in faster ice velocities, and subsequent thinning of the ice sheet margins. As the surface slope decreases, the area affected by increased surface melting and sliding migrates further inland, and the period of slow margin retreat is followed by very rapid retreat until the whole of the ice sheet back to the ice divide is undergoing surface melting and basal sliding (Parizek and Alley, 2004; Sole *et al*., 2008).

Sole *et al*. (2008) tested this hypothesis using surface elevation data for 25 tidewater and land-terminating glaciers in Southeast and West Greenland. They argue that surface elevation changes for the two types of glacier should be statistically the same if thinning and retreat is primarily caused by surface meltwater effects on ice flow. However, their results indicated that marine-terminating glaciers thinned significantly faster than land-terminating glaciers between 1993 and 2006, and retreat increased sharply after 1998. No such change in rate was observed for land-terminating glaciers, which thinned no more than would be expected based on observed ablation, suggesting that enhanced basal lubrication is not a significant influence on retreat at present (Sole *et al*., 2008). Two other studies that have included some land-terminating glaciers in the data set also observed that these underwent only minimal retreat during the whole of the 1990s and 2000s, compared to neighbouring tidewater outlets (Howat *et al.*, 2008; Moon and Joughin, 2008). This suggests that a change in a controlling mechanism affecting only tidewater glaciers occurred during the late 1990s (Sole *et al*., 2008).

It has been suggested that recent rapid dynamic thinning may be a consequence of ocean warming (Hanna *et al.,* 2009; Joughin *et al.*, 2008; Holland *et al.*, 2008; Sole *et al*., 2008; Pritchard *et al*., 2009). An increase in ocean temperatures will lead to increased basal melt at the terminus, which can cause it to break up. This in turn reduces the buttressing effect that puts a back pressure on upstream parts of the glacier, and leads to increased longitudinal stretching and faster velocities of glacier flow (Sole *et al*., 2008; Holland *et al*., 2008; Joughin *et al*., 2008). Data on surface and sub-surface ocean temperatures for recent decades indicates that rapid warming of southeast and southwest ocean waters occurred during the late 1990s and early 2000s, which corresponds to the rapid acceleration of tidewater glacier retreat in these regions (Holland *et al*., 2008; Hanna *et al*., 2009; see Figure 2.6). In contrast, air temperatures have increased steadily during the past two decades, and have not undergone any rapid increase which might explain dramatic speed-up and retreat of tidewater glaciers (Holland *et al*., 2008).

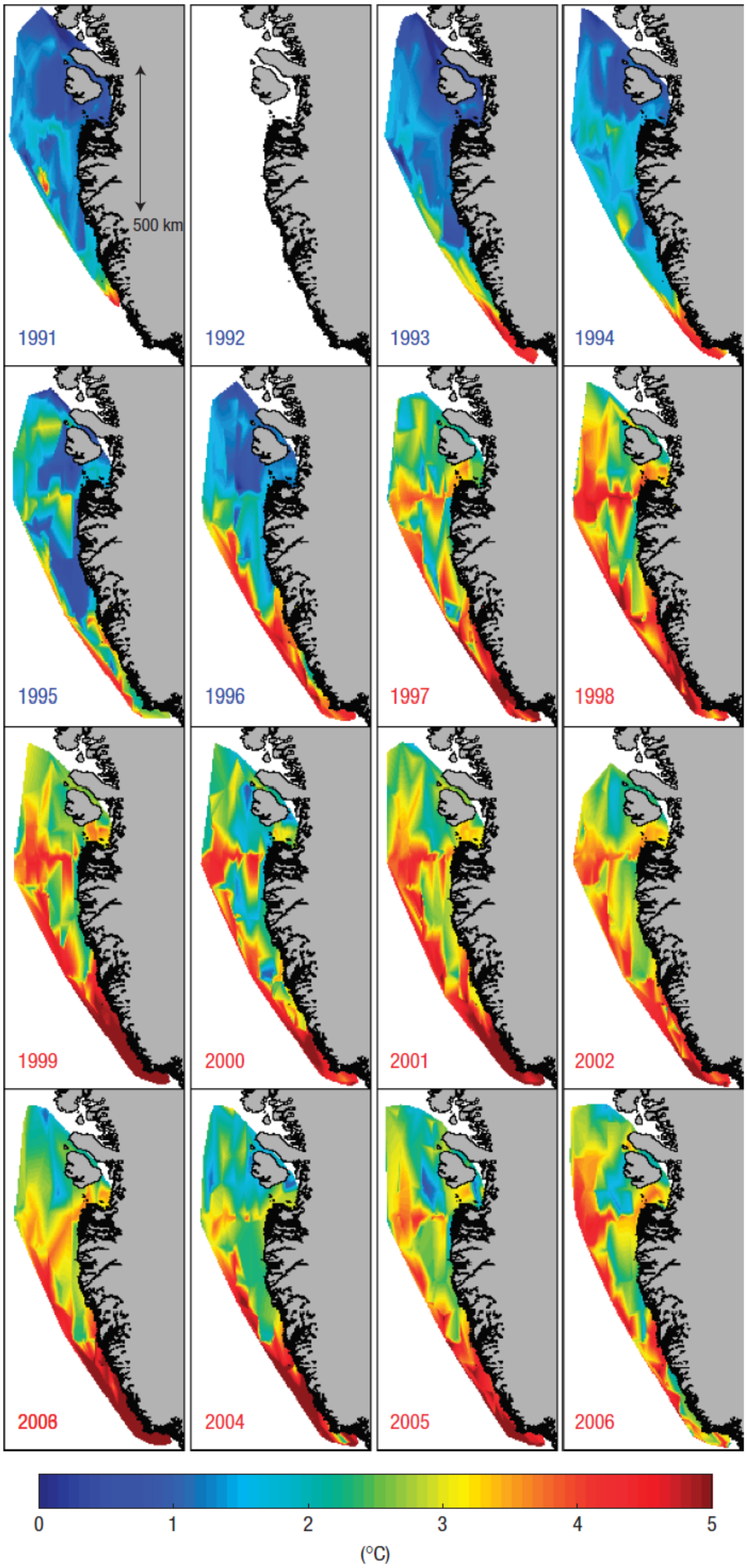


Figure 2.6: Maps showing sub-surface ocean temperatures over the West Greenland continental shelf between 1991 and 2006, based on data from trawl fisheries. The change from blue to red number years highlights the flooding of Disko Bugt with warm water. Figure from Holland *et al*. (2008: 663).

The rapid thinning and retreat of Greenland's outlet glaciers has led to concerns that their contribution to global sea level rise is likely only to increase in the coming years (Joughin, 2006; Joughin *et al.*, 2004; Pritchard *et al.*, 2009; Khan *et al.*, 2010). However, some authors have suggested that the recent acceleration of glacier retreat may only be a temporary phenomenon, and will not continue indefinitely. Csatho *et al.* (2008), for example, have put the recent rapid retreat of Jacobshavn Isbrae into context by examining its behaviour in detail since the LIA. They conclude that the glacier has both thickened and thinned erratically during this time period.

The majority of the recent research into glacier fluctuations has been based on tidewater glacier samples, which are well known to undergo regular cycles of advance and retreat irrespective of climate conditions (Warren, 1991). As Nick *et al.* (2009) point out, the vast majority of Greenland's tidewater outlets sit in short, shallow fjords, and this limits their potential for significant mass loss. If tidewater glaciers continue to retreat at present rates, they will slow down dramatically once grounded on the bedrock. Sole *et al*. (2008) estimate that a retreat of 2-5% of the whole ice sheet would result in all margins and outlet glaciers being out of direct contact with the ocean, although a non-uniform retreat could lead to some glaciers in long, deep fjords remaining as marine-terminating (e.g. Petermann Gletscher in Northern Greenland). Further examination of the long-term behaviour of land-terminating outlet glaciers of the Greenland Ice Sheet is, therefore, important for developing predictions of future retreat and mass loss.

2.3.4 Summaries of long-term Greenland Ice Sheet glacier fluctuations

Due to the large size of the Greenland Ice Sheet, and the overwhelming number of glaciers that drain it, studies of outlet glacier changes for the whole ice sheet during the twentieth century are rarely undertaken. A detailed inventory of all glaciers was published by Weidick *et al.*, (1992), but only for the Southwest, Southern West and Central West sections of Greenland (59° - 71° N). This database contains detailed maps and information on characteristics of all 5606 glaciers within this region, ranging from snowfields to outlet glaciers of the inland ice, and is a valuable resource for anyone conducting glaciological research in West Greenland. However, it does not contain any information on how glacier size or length has fluctuated over time. The only work to consider glacier fluctuations for the whole ice sheet throughout the twentieth century is the 'Satellite Image Atlas of Greenland' (Weidick, 1995). This paper reviews the historical accounts, observations, aerial photographs and published research into glacier fluctuations, to summarise early twentieth century trends. It supplements this with more recent imagery from the Landsat satellites (launched in 1972), to give an overview of how each region has behaved during the whole of the twentieth century. The paper is extremely informative, as it puts regional trends into context with changes that have happened in other sectors of the ice sheet.

2.3.5 Twentieth century trends in Greenland Ice Sheet mass balance

Towards the end of the twentieth century, many researchers moved away from focussing purely on outlet glacier length changes, towards assessing the mass balance of the ice sheet and its outlet glaciers. Examination of long term trends was difficult, however, due to a lack of satellite data or field measurements prior to 1970. Only three glaciers have records that extend beyond this period, with eight having data during the 1970s. A summary of these suggested that all had remained fairly stable during that decade (Weidick, 1984).

Early assessments of whole ice sheet mass balance were made by Zwally *et al.* (1989), who used altimetric data from the recently lauched Seasat and Geosat satellites to examine changes in mass balance of the southern part of the Greenland Ice Sheet since the 1970s. They concluded that the data showed a thickening of the ice sheet during this period (Zwally *et al.*, 1989). It was later suggested that this growth could be the result of satellite errors (Douglas *et al.*, 1990), but ablation stake measurements made every day for seven years by Braithwaite and Oleson (1993) also indicated that the ice sheet had thickened in South West Greenland.

In some instances, an examination of mass balance changes over longer time periods was made possible by using survey data compiled by early expeditions. For example, Paterson and Reeh (2001) used elevation data derived from trigonometric levelling during the 1953-1954 British North Greenland Expedition across the ice cap, to assess changes in North Greenland. When the data were compared to elevations derived from remotely sensed radar altimetry for 1995, they indicated that the Northwest ice sheet margin had thinned significantly, even close to the centre of the ice sheet. In contrast, the Northeast sector of the ice sheet appeared to have thickened slightly during this period.

Huybrechts (1994) used a model to examine changes in ice sheet thickness over the past 200 years. The data indicated that much of the ice sheet had a stable mass balance or thickened slightly over this period (see Figure 2.7), and growth was particularly significant in the southwest. He concluded that this is due to the continued adjustment of the ice sheet to the steeper slopes generated by rapid margin retreat in this region during the last glacial-interglacial transition. The thinning in many other marginal areas is most likely the result of increased ablation following the LIA (Huybrechts, 1994).

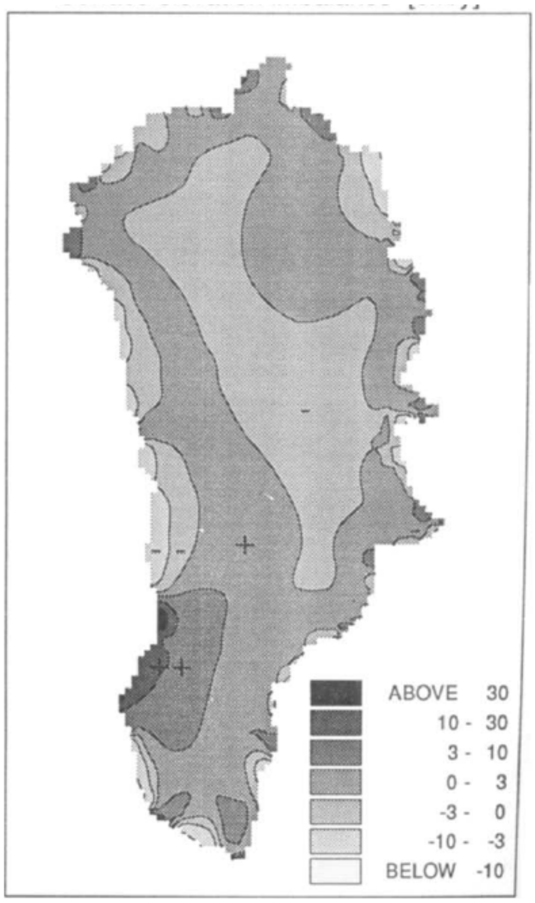


Figure 2.7: Rate of surface elevation change averaged over the last 200 years. Positive values indicate thickening and negative are thinning (Huybrechts, 1994: 44).

Mass balance changes of the Greenland Ice Sheet since the LIA have been modelled in more detail by Wake *et al*. (2009). Their results indicate that the ice sheet surface mass balance anomalies were positive overall between 1866 and 1926 as a result of the relatively low air temperatures during this period (Figure 2.8). A prolonged period of negative mass balance anomalies is observed between 1926 and 1960, which can be explained by the high air temperatures recorded between the 1920s and 1950s. Since the 1960s, mass balance has been more varied, but negative overall, especially after 2000 (Wake *et al*., 2009).

These results are supported by independent modelling of twentieth century Greenland Ice Sheet mass balance undertaken by Fettweis *et al*. (2008). Their results also suggested that surface mass balance oscillated between positive and negative phases between 1960 and 1990, whereas the 1930s and 2000s were characterised by predominantly negative mass balance. Both Fettweis *et al*. (2008) and Wake *et al*. (2009) concluded that recent mass loss since the 1990s is not exceptional when compared to early twentieth century negative mass balance. Indeed, Wake *et al*. (2009) go further, and suggest that the recent changes are not the result of anthropogenic global warming, as is commonly asserted, but are part of a natural cycle of sub-decadal mass balance fluctuations. The spatial variability of long-term Greenland Ice Sheet mass balance changes has also been examined by Wake *et al*. (2009), Ettema *et al*. (2009), Hanna *et al*. (2005) and van den Broeke *et al*. (2009), amongst others, and their results indicate that Southeast Greenland has lost the most mass overall since 1958 (see Figures 2.9).

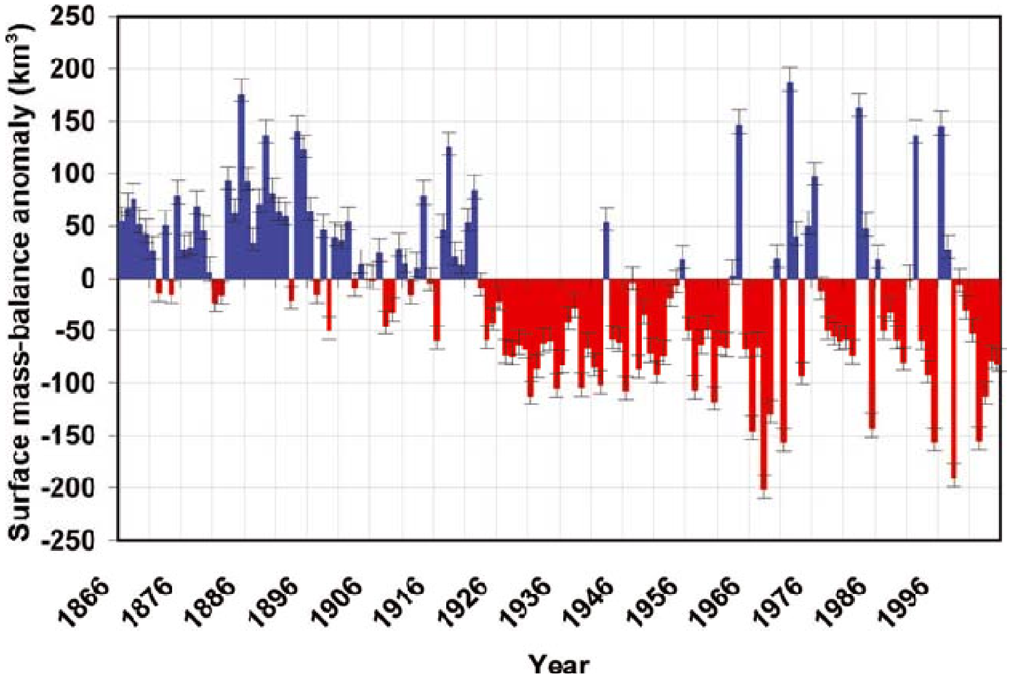


Figure 2.8: Annual global surface mass balance anomalies modelled for the period 1866-2005, where blue indicates positive and red negative mass balance (from Wake *et al*., 2009: 181).

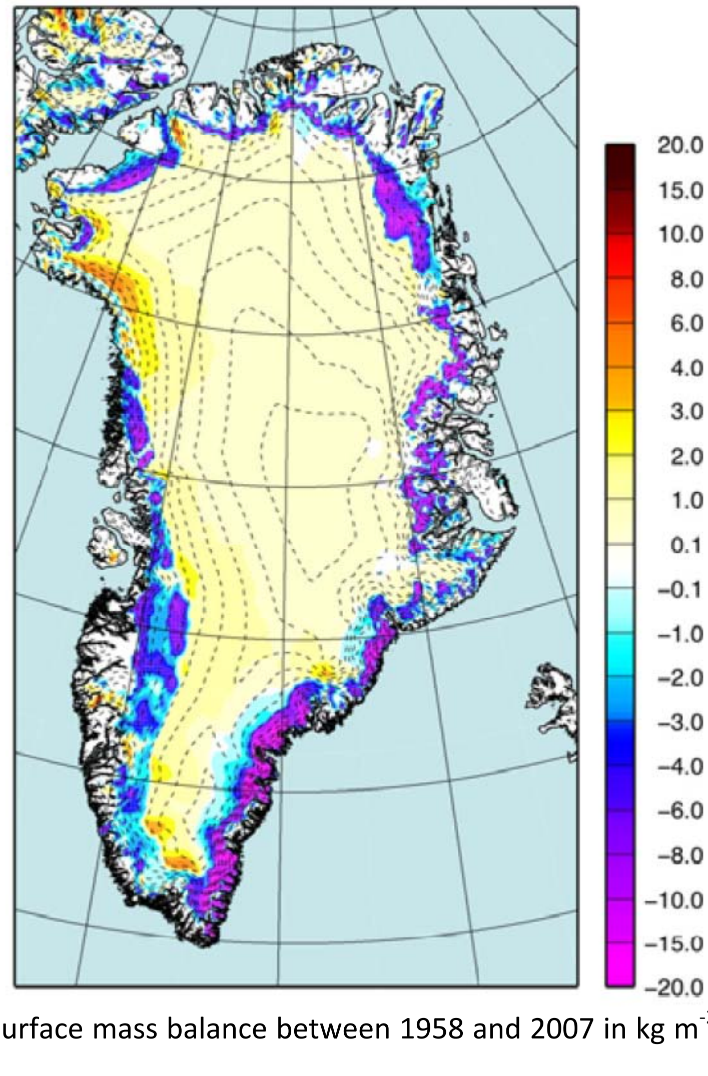


Figure 2.9: Modelled surface mass balance between 1958 and 2007 in kg m^{-2} (from Ettema *et al.,* 2009: 4).

2.3.6 Greenland Ice Sheet mass balance changes since the 1990s

Long-term modelling studies indicated that the Greenland Ice Sheet has been consistently losing mass since the 1990s. This is supported by remotely sensed estimates of mass balance from satellite altimetry and the Gravity Recovery and Climate Experiment (GRACE), which show that the margins have been losing mass at an ever-increasing rate during the past two decades (Krabill *et al.*, 2000; Rignot *et al.*, 2001; Velicogna, 2009; Khan *et al.*, 2010). In addition, satellite radar interferometry and RADARSAT data have been used to show that flow velocity at the margins also increased after the 1990s (Rignot and Kanagaratnam, 2006; Joughin *et al*., 2010), whilst ICESat laser altimetry data indicates that many margins are thinning (Pritchard *et al*., 2009).

It is generally accepted that the accelerated mass loss and thinning of the margins started in the southern regions of the ice sheet during the mid-1990s and subsequently spread to North Greenland, which began thinning rapidly in the mid-2000s (Pritchard *et al.*, 2009; Velicogna, 2009; Khan *et al.*, 2010; see Figure 2.10). Van den Broeke *et al*. (2009) have attempted to quantify the relative contributions of surface mass balance and ice discharge to overall mass balance losses between 2003 and 2008 (See Figure 2.11). The data indicate that surface mass balance changes account for the majority ice sheet mass loss in Southwest, North and East Greenland, whereas mass loss in Southeast Greenland is dominated by ice discharge, and in Central and Northern West Greenland mass loss is divided equally between the two components. Van den Broeke *et al*. (2009) suggest that ice discharge in the North and Northeast is very low because of the low accumulation rates, whilst the large ablation area and few tidewater outlet glaciers in the Southwest explain the dominance of surface mass loss in this region. In contrast, the Northwest region has numerous tidewater glaciers, so the ice discharge contribution to mass loss is much higher. The dominance of ice discharge on mass loss in the Southeast is partly the result of high accumulation and lots of tidewater outlet glaciers (Van den Broeke *et al*., 2009). In addition, the ice sheet in East Greenland has a relatively steep surface slope, so the ablation zone is consequently much narrower (~11 km) than in West Greenland (<150 km), and this limits the potential surface mass loss (Ettema *et al*., 2009; Wake *et al*., 2010).

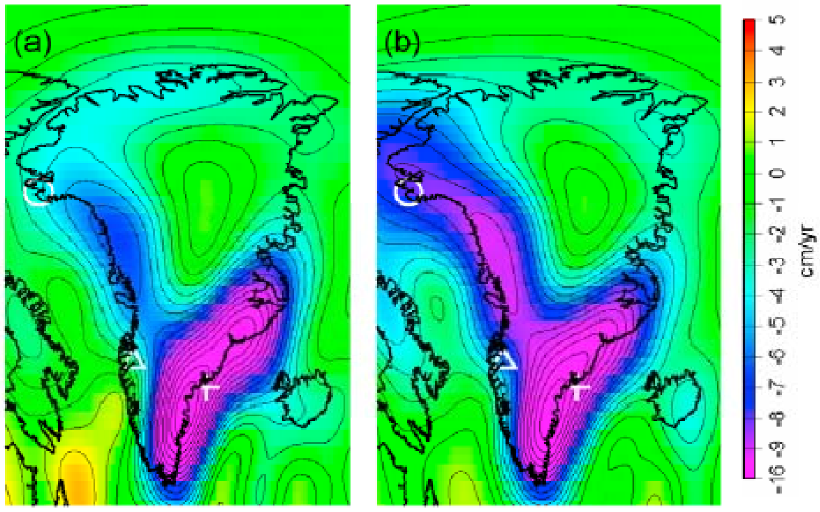


Figure 2.10: The rate of mass loss in cm per year water equivalent thickness determined from monthly GRACE gravity field solutions for (a) February 2003-February 2007, and (b) February 2003-June 2009. Blues and purples indicate more rapid mass loss. Taken from Khan *et al.* (2010: 3).

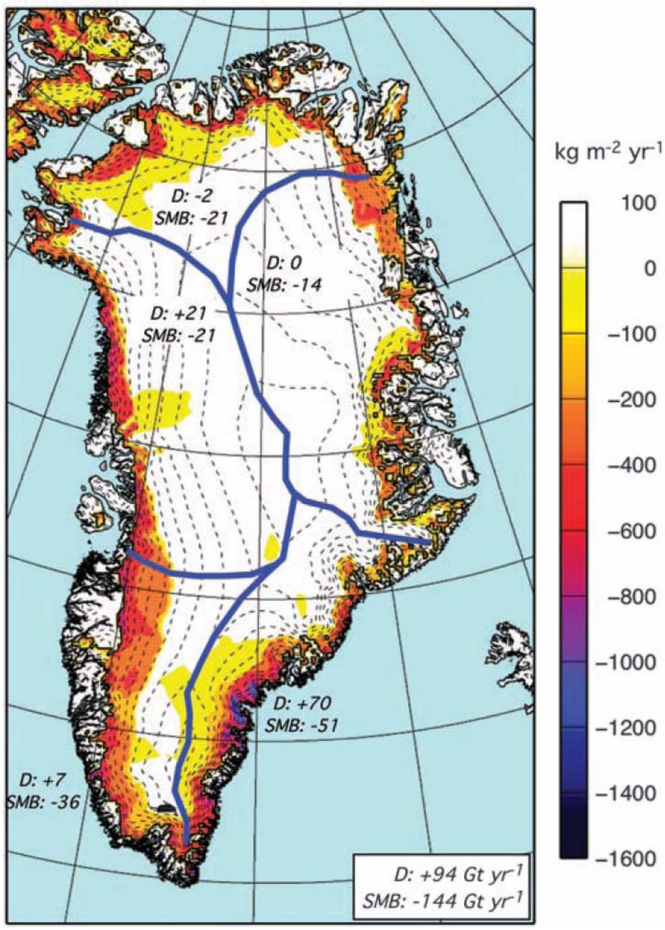


Figure 2.11: Mass balance changes from 2003-2008 estimate using GRACE measurements. The numbers are calculated basin-integrated mass loss rates in Gt a^{-1} due to surface mass balance (SMB) and ice discharge (D). Values for the whole ice sheet are shown in the bottom right-hand corner. Colours represent the rate of surface mass change (from Van den Broeke *et al.,* 2009: 985).

2.3.7 Summary of Greenland Ice Sheet behaviour

Studies of fluctuations in the terminus positions of the outlet glaciers that drain the Greenland Ice Sheet suggest that most have retreated during the twentieth century, having reached their historical maximum at the end of the nineteenth century. The periods from 1900-1920 and 1940-1950 were characterised by low annual rates of retreat, whereas during the periods from 1920-1940 and 1990-2010 many glaciers retreated rapidly. Some sections of the ice sheet may have advanced after the 1950s. In general, glaciers in Northern Greenland and East Greenland are more stable than those in Southeast, West or Northwest and Northeast Greenland. Estimates of twentieth century mass balance suggest that different sectors of the ice sheet may have thickened and thinning at different times, particularly between 1960 and 1990. In the 1930s and 2000s most of the ice sheet steadily lost mass, with the 1930s likely experiencing the highest rates of mass loss in historical time. Studies of tidewater glaciers in recent years have indicated that rapid acceleration of thinning and retreat has occurred, but it is unclear whether this is the start of a long-term trend, or a brief cyclical fluctuation. Terminus environment has shown to be an important control on glacier behaviour, and this is supported by observations of land-terminating glaciers, which have shown no increase in rates of retreat during the past two decades.

2.4 Independent ice cap and mountain glacier behaviour in Greenland

2.4.1 Independent glacier fluctuations around the whole of Greenland during the twentieth century

The first scientific observations of independent ice caps and mountain and valley glaciers (henceforth referred to as 'independent glaciers') in Greenland were made as part of the early twentieth century expeditions to survey the ice sheet and coasts (see Section 2.3.1 above). Some later studies used these observations to reconstruct independent glacier fluctuations alongside those of the ice sheet, with conflicting results. For example, Davies and Krinsley (1962) found that independent glaciers in North Greenland had remained stable during the first half of the twentieth century, whilst the ice sheet retreated. In contrast, Weidick (1968, 1984) observed that independent glaciers and the main ice sheet in West Greenland both followed the same pattern of general retreat, with occasional advances.

More recently, studies of glacier behaviour throughout the whole of the twentieth century have observed that an almost universal retreat of all North and West Greenland glaciers has occurred (Weidick, 1995; Weidick and Morris, 1998). However, several ice caps in North Greenland are known to have expanded or remained stable (Weidick and Morris, 1998), which could explain Davies and Krinsley's (1962) findings. The retreat of West Greenland independent glaciers slowed down in later decades, to the point of advance in some cases during the 1960s, as was also observed for the main ice sheet (Weidick *et al.*, 1992; see Section 2.3.1). Observations of independent glacier behaviour in East Greenland are very limited, but a general twentieth century recession appears to have taken place (Weidick, 1995).

Whilst all of the studies cited above have included examinations of independent glacier fluctuations, their focus was on the main ice sheet. Very few studies have looked specifically at independent glaciers, or undertaken a detailed examination of their behaviour in relation to the main ice sheet. An exception is research by Gordon (1981), who examined the response times of independent and main ice sheet outlet glaciers in Central West Greenland. He concluded that the small, independent mountain glaciers showed a lag time of ~10 years in response to climate forcing, whereas the main ice sheet outlet glaciers lagged climate by 20-30 years. Despite these interesting observations, research focussing on independent glacier fluctuations has remained scarce in recent decades.

The only detailed study of twentieth century changes was undertaken on Disko Island in Central West Greenland by Yde and Knudsen (2007), who used aerial photographs, historical data, meteorological data and Landsat and SPOT imagery to assess the influence of size, altitude and orientation on both surging and non-surging glaciers. They found that the glaciers had retreated during the twentieth century, with a period of rapid retreat from 1964-1985. This behaviour is in contrast to many main ice sheet outlet glaciers in West Greenland, which advanced during this time period (Weidick *et al*., 1992; Weidick, 1995). The authors suggest that this behaviour is the result of differing response times of the different glacier classes to climate change (Yde and Knudsen, 2007).

The only other recent paper to focus on independent glaciers in Greenland is a review of Pleistocene and Holocene fluctuations published by Kelly and Lowell (2009). The authors summarise previous research to give an overview of regional changes. They conclude that all independent glaciers, with the exception of some in North Greenland, are currently receding from their LIA maximum extents. There is also some evidence to suggest that many may have experienced slower retreat or advanced during 1960-1980. Although data are scarce, similar patterns of glacier fluctuations are observed in all regions.

2.4.2 Independent glaciers in the northwest study area

The last detailed survey of independent glaciers in the Northwest was carried out by Davies and Krinsley (1962), who studied 35 local ice cap outlet glaciers within the area surrounding the North Ice Cap. They found that most glaciers were at their maximum historical extent c.1880-1900. Between 1900 and 1960, 20 % of the glaciers studied were stationary, 80 % were retreating and none had advanced. The only detailed mass balance studies within the northwest study area were carried out on the 'Red Rock' ice cliff, along the eastern margin of the North Ice Cap (see Chapter 1, p.6 for map). The ice cliff was surveyed several times between 1955 and 1965, and the results indicated that it had advanced during this period (Goldthwait, 1960, 1961, 1971). The expansion of the North Ice Cap is an anomaly in this area, however, with most Northwest ice caps observed to be shrinking between the LIA maximum and 1960s (Weidick, 1995). It is not known exactly how they have behaved in the latter half of the twentieth century.

2.4.3 Independent glaciers in the southwest study area

Glacier fluctuations in West Greenland have been more extensively studied and observed than in any other region, with records for some individual outlets dating back 150 years (Weidick, 1995). The Sukkertoppen ice cap was first surveyed in detail by an expedition from Oxford University, who investigated a number of factors that might govern ice cap behaviour, such as ablation, accumulation and rate of outlet glacier flow (Sugden and Mott, 1940). Based on this research of a smaller-scale, 'model' ice cap, they hoped to better understand the behaviour of the main ice sheet. Further glaciological studies on Sukkertoppen were undertaken independently by Bull (1963) and Henry and White (1964), who measured ice thickness, precipitation and temperature patterns across the ice cap. Based on their results, Bull (1963) suggested that the ice cap has a temperate regime, whilst Henry and White (1964) classified it as Arctic. It is likely that the ice cap displays characteristics of both regimes in different locations, which would account for this discrepancy (Loewe, 1966).

Lichenometric dating of terminal moraines suggests that the timing of maximum historical extent of independent glaciers varied widely, from the 1700s for some western ice cap outlets, to c.1850-1890 for many eastern outlets (Beschel and Weidick, 1973). In general, outlet glaciers of the local ice caps retreated between ~1890 and 1940, with the maximum rate of retreat occurring between 1920 and 1940. Some glaciers re-advanced somewhat during the 1940s and 1950s (Gordon, 1981; Weidick, 1968, 1995), before significant overall retreat occurred during the 1960s and early 1970s. This was followed by another general re-advance during the late 1970s (Gordon, 1981). No detailed examination of independent glacier trends since the 1980s has yet been made.

2.4.4 Summary of independent glacier behaviour during the twentieth century

Independent glaciers in Greenland have not been researched as extensively the main ice sheet, but the majority appear to have retreated during the twentieth century, although recent changes are less well documented. The exceptions to this trend are some ice caps in North Greenland, which have advanced or remained stable. Research suggests that independent glaciers may respond more quickly to climate changes than the main ice sheet outlet glaciers, by ~20-30 years. Studies focussing on the northwest study area suggest that glaciers reached their maximum historical extent c.1880-1900, and then retreated until at least 1960. The exception to this is the North Ice Cap, which was observed to expand during the first half of the century. In the southwest study area, lichenometric dating suggests that most glaciers reached their maximum historical extent between c.1850 and 1890. Overall retreat then occurred between 1890 and 1980, although with periods of re-advance during the 1940s, 1950s and 1970s.

2.5 Greenland climate during the twentieth century

The first meteorological stations in Greenland were set up in c.1873, at Upernavik, Illulissat (Jakobshavn), Nuuk (Godthab) and Narsarssuaq, which are all locations on the west coast (Cappelen, 2006). Many more stations were set up throughout the 20^{th} century at locations around the whole of the Greenland coastline, to measure air temperature, precipitation, air pressure, cloud cover and other climatic variables (Carstensen and Jorgensen, 2010). In the following sections, trends in air temperature, precipitation and sea surface temperatures during the 20^{th} century will be briefly summarised.

2.5.1 Air temperatures

A review of temperature records between 1873 and 2001 was made by Box (2002), who concluded that temperatures in Greenland generally increased from 1885-1947 and 1984-2001, and decreased from 1955-1984 (see Figure 2.12). Unlike the rest of the Northern hemisphere the decade from 1991-2000 was not the warmest on record, despite a mean increase in temperature of 2-4°C. In addition, Box *et al.,* (2009) found that the temperature increase from 1919-1932 was 33% greater than that from 1994-2007. The highest air temperatures were recorded in 1932, 1947, 1960 and 1941, whilst the coldest years were 1918, 1984, 1993 and 1972 (Box, 2002). Temperatures in Greenland are dominated by winter variations, and fluctuations are the result of changes in the North Atlantic Oscillation, sea ice cover and volcanic eruptions. West and East Greenland often experience different trends in air temperature (Box, 2002).

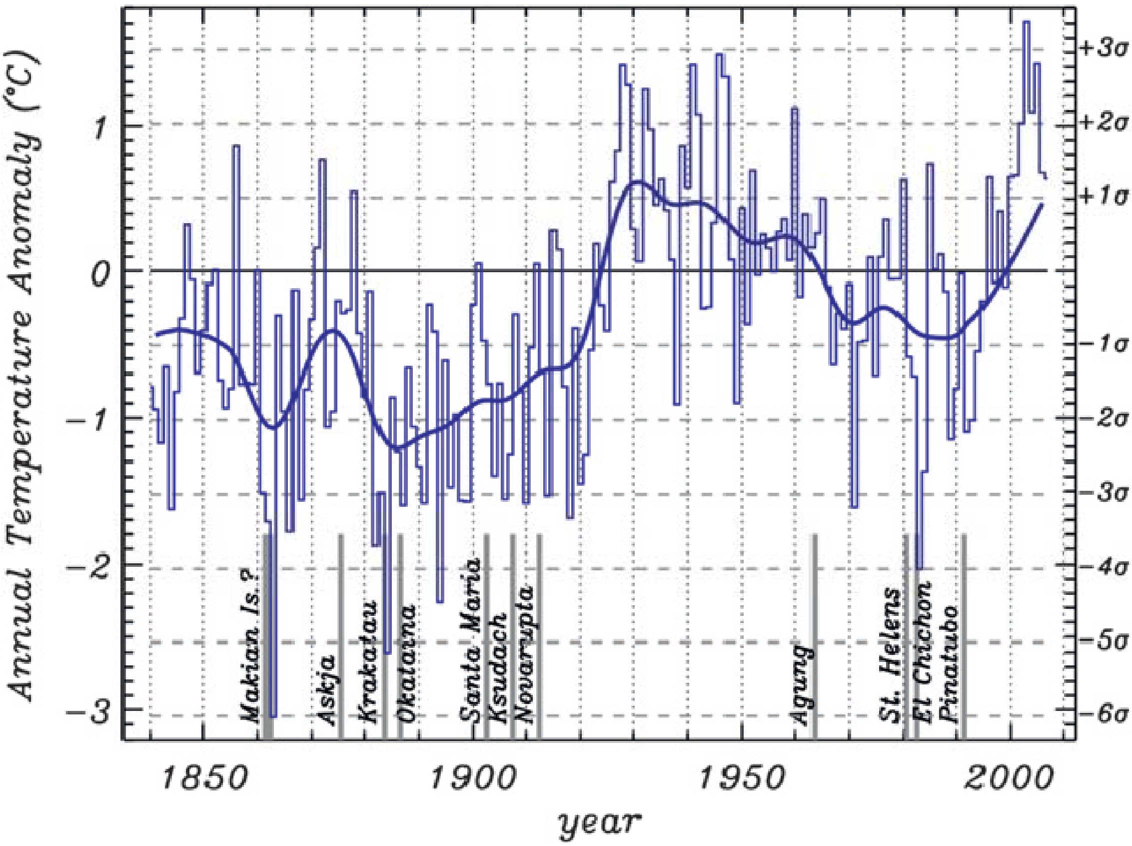


Figure 2.12: Mean annual air temperature anomalies in Greenland with respect to the 1951-1980 base period. Grey lines indicate major volcanic eruptions (from Box, 2009: 4042).

2.5.2 Precipitation

Precipitation trends in Greenland have been reviewed most recently by Ohmura and Reeh (1991). Precipitation data from meteorological station around the coast reveal that there is a strong west-east gradient, with East Greenland much wetter than West Greenland. Southeast Greenland receives the most precipitation, on average, as the south-easterly winds are forced to rise over the ice sheet. Northeast and Southwest Greenland, and the area around Sondre Stromfjord in the southwest study area, are particularly dry regions. In the case of Sondre Stromfjord, this is because a ridge in the ice sheet to the south creates a precipitation shadow. The mean annual precipitation for Greenland is approximately 340 mm w.e. (Ohmura and Reeh, 1991).

2.5.3 Sea surface temperatures

Sea surface temperature data for the first half of the 20th century is limited, and comes primarily from individual expeditions and fishing boats (Buch, 2000). However, it is possible to use these and later, more numerous, data points to interpolate sea surface temperatures around Greenland since the 19th century (Rayner *et al.*, 2003). Temperatures vary significantly around the coastline, but appear to have decreased overall between 1870 and 1920, and increased from 1920-1930 and from the 1970s onwards (Hanna *et al.,* 2009). Particularly rapid ocean warming has been reported during the 1990s and 2000s (Holland *et al.,* 2008; Hanna *et al.,* 2009).

Chapter 3

Methods

3.1 Introduction

Whilst scientists have been monitoring glacier terminus positions since the 1800s, it has been the advent, rapid improvements and diversification of remote sensing techniques that has enabled fluctuations to be studied in detail worldwide (Haeberli, 1998). Mapping changes from satellite images and aerial photography is easier, faster, cheaper and just as accurate ground observations (Hall *et al*., 2003), with the crucial advantage that regular, detailed observations are available for thousands of glaciers worldwide over many years, as opposed to only a handful of long-term ground observations. The purpose of this chapter is to describe the types of imagery and data processing methods used to map glacier fluctuations in west Greenland. Section 3.2 outlines the different types of aerial and satellite imagery used in the study, with detailed descriptions of their specifications and the reasons why they were chosen. Section 3.3 then describes how the different types of imagery were prepared for mapping. Section 3.4 discusses the range of mapping techniques available, before outlining in detail the process of mapping the glaciers, and Section 3.5 describes how the data were analysed. Finally, Section 3.6 explains how the various errors involved in image processing and mapping were quantified and combined to give estimates of total error.

3.2 Data sources

Previous studies have used a huge range of different types of satellite imagery to study glacier fluctuations, including Landsat, Corona, ASTER, IKONOS, Hexagon, SPOT, MODIS and SAR (e.g. Paul *et al*., 2002; Zhou *et al*., 2002; Silverio and Jaquet, 2005; Moon and Joughin, 2008). Each satellite is designed to perform different tasks at different spatial and temporal scales, and each has both benefits and drawbacks when used for mapping. In this study, the majority of mapping will be done using Landsat imagery, because it is the longest-running satellite, with images freely available for the whole period between 1972 and 2007. ARGON images from the 1960s, and aerial photographs from the 1940s and 1950s, will be used to extend the dataset over a much longer time period. In addition, most recent glacier fluctuations will be mapped from 2009 ASTER imagery. Detailed descriptions of each type of imagery and their suitability for mapping are given in the following sections.

3.2.1 Landsat

Landsat is the longest-running satellite image acquisition program in the world, having taken images of the Earth's surface continuously since the first satellite was launched in July 1972. The satellites have near–global coverage (<90°), moderate resolution of between 15-80 m, and are freely available to download on the internet, making them a popular and very useful tool for investigating glacier fluctuations at long timescales (e.g. Sidjak and Wheate, 1999; Paul, 2002; Silverio and Jaquet, 2005). In this study, Landsat images were used to map glacier fluctuations between 1972 and 2007 at 6 (southwest) and 7 (northwest) time steps. Images were acquired from the United States Geological Survey (USGS) 'Earth Explorer' web interface (http://earthexplorer.usgs.gov), and full details are given in Table 3.1.

In total, there have been seven Landsat satellites launched, with the later versions carrying increasingly sophisticated imaging systems to produce better quality and higher resolution images (see Table 3.2). The principal imaging system on the earliest satellites (Landsats -1, -2 and -3) was a Multispectral Scanner (MSS), which collected data in four spectral bands: green, red and two infrared, at 79 m ground resolution. These satellites also carried a secondary imaging system, the Return Beam Vidicon (RBV), which provided an additional panchromatic band with 80 m resolution. There is only a limited amount of MSS imagery available for Greenland in the 1970s and early 1980s, and many of the available scenes are obscured by cloud or snow cover. This, together with the coarser spatial resolution compared to more recent imagery (e.g. TM, ETM+), meant that only a small sample of glaciers could be accurately mapped during these years. The collection of MSS data ended in 1992 after it was superseded by the Thematic Mapper (TM) system, which was carried on Landsats -4 and -5. The TM sensor had better spectral and spatial resolution than the MSS, so was capable of detecting more of the electromagnetic spectrum and of imaging the ground at a higher resolution of 30 m. The instrument had seven spectral bands: blue, green, red, near-infrared and two infra-red. This means that images can be viewed in a range of band combinations to distinguish surfaces with different spectral signatures, such as vegetation and water.

Region	Satellite	Date	Path and row	Scene ID
SW	Landsat-1 MSS	06/08/1973	009 013	LM10090130073218
	Landsat-5 TM	11/08/1985	010 013	LM50100131985223
		14/08/1987	005 015	LT50050151987226
		20/07/1987	006 014	LT50060141987201
		25/06/1987	007 013	LT50070131987176
		25/06/1987	007 014	LT50070141987176
		16/07/1992	009 013	LT50090131992197
		11/09/1993	009 014	LT50090141993192
	Landsat-7 ETM+ SLC-on	03/08/2001	006 014	LE70060142001215
		03/08/2001	006 015	LE70060152001215
		09/07/2001	007 013	LE70070132001190
		09/07/2001	007 014	LE70070142001190
		14/06/2001	008 014	LE70080142001165
		07/07/2001	009 013	LE70090132001188
	Landsat-7 ETM+ SLC-off	04/08/2007	006 013	LE70060132007216
		04/08/2007	006 014	LE70060142007216
NW	Landsat-1 MSS	26/07/1972	034 005	LM10340051972267
	Landsat-2 MSS	21/06/1975	036 004	LM20360041975172
	Landsat-5 TM	28/09/1987	032 005	LT50320051987271
		28/08/1995	029 005	LT50290051995240
	Landsat-7 ETM+ SLC-on	23/08/1999	028 006	LE70280061999235
		02/07/1999	030 005	LE70300051999186
		05/07/1999	030 006	LE70300061999186
		24/07/1999	035 004	LE70350041999205
		24/07/1999	035 005	LE70350051999205
		02/07/2002	033 004	LE70330042002183
		01/08/2002	035 004	LE70350042002213
	Landsat-7 ETM+ SLC-off	19/08/2007	031 005	LE70310052007231
		13/08/2007	037 004	LE70370042007225

Table 3.1: Details of Landsat images used, in chronological order for each study area.

System	Operating period	Instruments	Spectral bands (µm)	Resolution (metres)	Altitude (km)	Repeat interval (days)	Scene size (km)
Landsat -1	23/07/1972 - 06/01/1978	RBV	Bd 1 (475-575 nm) Bd 2 (580-680 nm) Bd 3 (690-830 nm)	80	917	18	170 x 185
		MSS	Bd 4 (0.5-0.6) Bd 5 (0.6-0.7) Bd 6 (0.7-0.8) Bd 7(0.8-1.1)	80			
Landsat -2	22/01/1975 - 25/02/1982	RBV	Bd 1-3 as above	80	917	18	170 x 185
		MSS	Bd 4-7 as above	80			
Landsat -3	05/03/1978 - 31/03/1983	RBV	Bd 1-3 as above	30	917	18	170 x 185
		MSS	Bd 4-7 as above Bd 8 (10.4-12.6)	80			
Landsat -4	16/07/1982 - 08/1993	MSS	Bd 4-7 as above	80	705	16	170 x 185
		TM	Bd 1 (0.45-0.52) Bd 2 (0.52-0.60) Bd 3 (0.63-0.69) Bd 4 (0.76-0.90) Bd 5 (1.55-1.75) Bd 6 (10.4-12.5) Bd 7 (2.08-2.35)	30			
Landsat -5	01/03/1984 - present	MSS	Bd 4-7 as above	80 30	705	16	170 x 185
		TM	Bd 1-7 as above				
Landsat -6	05/10/1993- failed on launch	ETM	Bd 1-7 as above Bd 8 (0.52-0.90)	30 (ms) 15 (pan- Bd 8)	705	16	170 x 185
Landsat -7	12/1998 - present	ETM^+	Bd 1-7 as above Bd 8 (0.52-0.90)	30 (ms) 15 (pan- Bd 8)	705	16	170 x 185

Table 3.2: Specifications of the different Landsat satellites; (ms) = multispectral bands, (pan) = panchromatic bands (from NASA (2010), http://landsat.gsfc.nasa.gov).

An improved version of the TM system, the Enhanced Thematic Mapper (ETM), was developed for Landsats -6 and -7. This sensor collects data in the same seven spectral bands at the same resolution as the TM, but has an additional panchromatic band with ground resolution of 15 m. The high resolution of this imagery was compromised, however, in May 2003 when the Scan Line Corrector (SLC) on Landsat-7 failed. This mechanism compensates for the forward motion of the satellite, to remove the resulting 'zigzag' effect on the system's line of sight. Without an operating SLC the images produced suffer from areas of duplication and an estimated 25% data loss, which is worst near the edges (see Figure 3.1). These gaps have subsequently been filled by the USGS, by merging data from adjacent scenes or multiple time periods to give full scene coverage, with a binary bit mask provided with each image to allow users to identify the interpolated pixels. In practice, this gives images of the same high quality as before, but with stripes of lower quality data crossing them where detail is often obscured. Whilst this does present some problems for accurately defining glacier terminus position, error can be minimised by combining several adjacent scenes, thus allowing the majority of mapping to be done from image centres. When this was not possible, glaciers were mapped from the edge of an image, with care taken in areas of data interpolation. In general, it was found that only a few glaciers had to be discarded as impossible to map accurately, with most delineated as confidently as on other images. This is illustrated in Figure 3.1, which shows two images of glacier taken with and without a functioning SLC. As can be seen, whilst the SLC-off image has stripes of fuzzier interpolated data running across it the outline of the terminus can still be distinguished.

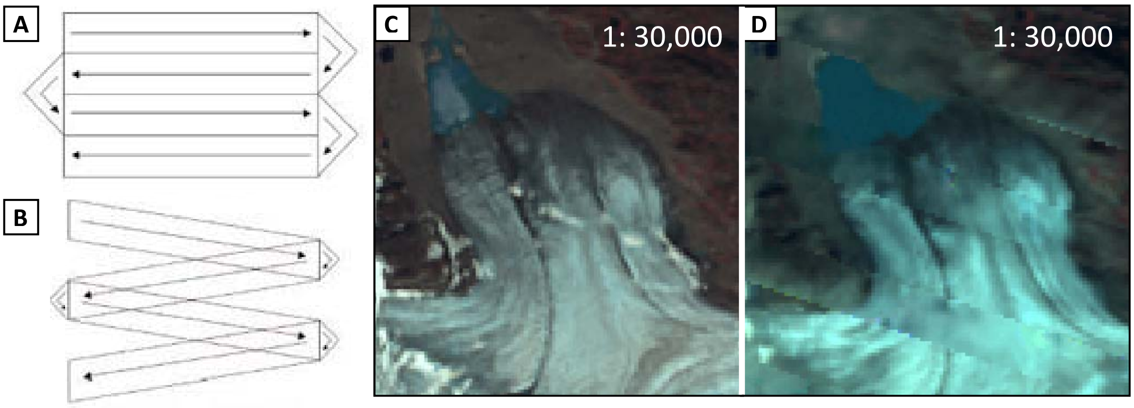


Figure 3.1: A comparison of Landsat-7 SLC-on and SLC-off data: a) Scan track with SLC functioning; b) Scan track with SLC off; c) Landsat ETM^+ image taken in 2001, before SLC failure; d) Landsat ETM^+ image taken in 2007, after SLC failure and with missing data interpolated. Note that the selected area comes from the edge of the scene. Diagrams A and B from USGS (2008).

3.2.2 ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is one of five sensors onboard the satellite Terra, which has been run as a collaborative effort by NASA and the Japanese Ministry of Economy Trade (METI) since its launch in 1999. The satellite has a sun-synchronous, near-polar orbit at an altitude of 705 km over a 16 day repeat interval (Van Ede, 2004). It is a more advanced satellite than Landsat, with data collected in 15 spectral bands that are divided into three systems: shortwave near-infrared (SNIR), thermal infrared (TIR) and visible and near-infrared wavelengths (VNIR; see Table 3.3). This project uses the three forward-facing VNIR bands to create an image that has ground resolution of 15 m. One drawback to using ASTER imagery, however, is that it has a smaller footprint than Landsat (120 x 150 km), which means that more images are required to cover the study area and, therefore, the pre-processing time is greatly increased. In addition, many of the ASTER scenes for West Greenland were not suitable for mapping, due to excessive cloud or snow cover and poor light quality; only a limited number of images were taken during the summer months, on a cloud free day, and during the hours of daylight. Somewhat counter-intuitively, Landsat-7 SLC-off was found to have better overall coverage and image quality. For these reasons, ASTER data were only used for 2009, when Landsat imagery is not yet available. Images were acquired from the NASA Warehouse Inventory Search Tool (https://wist.echo.nasa.gov), and full details are given in Table 3.4.

System	Band	Wavelength (µm)	Resolution (metres)	Direction
VNIR	1	0.520–0.600	15	Nadir
	2	0.630–0.690	15	Nadir
	3N	0.760–0.860	15	Nadir
	3B	0.760–0.860	15	Backward
SWIR	4	1.600–1.700	30	Nadir
	5	2.145–2.185	30	Nadir
	6	2.185–2.225	30	Nadir
	7	2.235–2.285	30	Nadir
	8	2.295–2.365	30	Nadir
	9	2.360–2.430	30	Nadir
TIR	10	8.125–8.475	90	Nadir
	11	8.475–8.825	90	Nadir
	12	8.925–9.275	90	Nadir
	13	10.250–10.950	90	Nadir
	14	10.950–11.650	90	Nadir

Table 3.3: Spectral characteristics and spatial resolution of ASTER (from Van Ede, 2004: 7)

There are two main types of ASTER data product available, Level 1a and Level 1b, which have undergone different amounts of pre-processing. For 2009, only the basic Level 1a data is currently available; this is unprocessed and full resolution data that comes with at-sensor radiance and geometric corrections calculated but not applied. When applied, the geometric corrections register the image to a co-ordinate system and the radiance corrections convert the digital numbers to radiance values, which can be further converted into surface reflectance or brightness temperature. For the purposes of this research, the ASTER image was geometrically corrected, but radiance corrections were not considered necessary.

Region	Date	Latitude	Longitude	Granule ID
NW	23/06/09	78.05	-69.44	AST_L1A#00306232009235021_06262009131345
	23/06/09	78.39	-71.50	AST_L1A#00306232009235030_06262009131355
	29/06/09	76.58	-66.86	AST_L1A#00306292009000814_07022009101741
	29/06/09	76.97	-68.51	AST_L1A#00306292009000823_07022009101750
	29/06/09	77.71	-72.17	AST_L1A#00306292009000841_07022009101807
	29/06/09	78.06	-74.06	AST_L1A#00306292009000850_07022009101817
	02/07/09	77.39	-66.34	AST_L1A#00307022009003857_07042009113306
	23/07/09	76.75	-71.46	AST_L1A#00307232009173208_07262009121239
	23/07/09	77.19	-70.05	AST_L1A#00307232009173159_07262009121232
	23/07/09	77.61	-68.54	AST_L1A#00307232009173150_07262009121224
	23/07/09	78.03	-66.96	AST_L1A#00307232009173142_07262009121217
	25/07/09	78.05	-72.22	AST_L1A#00307252009004520_07272009123413
SW	13/06/09	65.36	-50.27	AST_L1A#00306132009150723_06162009115329
	13/06/09	65.83	-49.77	AST_L1A#00306132009150732_06162009115338
	22/06/09	64.33	-49.64	AST_L1A#00306222009150132_06252009113724
	22/06/09	64.83	-49.17	AST_L1A#00306222009150123_06252009113715
	23/06/09	66.27	-49.35	AST_L1A#00306232009004152_06262009110842
	23/06/09	66.78	-49.81	AST_L1A#00306232009004201_06262009110852
	27/06/09	67.19	-50.45	AST_L1A#00306272009151907_06302009110248
	04/07/09	65.59	-52.87	AST_L1A#00307042009152538_07072009114232
	04/07/09	66.08	-52.35	AST_L1A#00307042009152529_07072009114225
	06/07/09	65.44	-52.47	AST_L1A#00307062009151323_07092009123240
	06/07/09	67.46	-50.41	AST_L1A#00307062009151248_07092009123204
	08/07/09	65.75	-51.59	AST_L1A#00307082009150100_07112009123131
	08/07/09	66.26	-51.14	AST_L1A#00307082009150051_07112009123121
	08/07/09	67.78	-51.14	AST_L1A#00307082009150051_07112009123121
	09/07/09	67.30	-50.25	AST_L1A#00307092009004155_07112009122524

Table 3.4: Details of ASTER granules used in the study. The co-ordinates given are for the centre point of each image.

3.2.3 ARGON

The ARGON missions were part of a series of US military reconnaissance satellites, including CORONA and LANYARD, which operated from August 1960 to May 1972. The CORONA satellites were the first to be developed, with the aim of gathering intelligence data from the former Soviet Union and other countries. They orbited the Earth at altitudes of 165-460 km taking black and white photographs, with ground resolution of 1.8 - 7.5 metres. In total, 144 CORONA satellites were launched, and they are divided into six categories: KH-1, KH-2, KH-3, KH-4, KH-4A and KH-4B, which indicate changes in the technology carried.

The ARGON satellites operated in a similar way to CORONA and were in use during the same period, from February 1961 to August 1964, with the designation KH-5. Whilst many of the missions were flown attached to the CORONA satellites, their primary purpose was to provide imagery for mapmaking rather than intelligence. Consequently, some of CORONA's high ground resolution was sacrificed to give images with a larger area footprint; full details of the satellite specifications are given in Table 3.5. The images used in this study are from the KH-5 9058A mission, with ground resolution of 89 m (northwest), and the KH-5 9066A mission, with resolution of 44 m (southwest; see Table 3.6 for details). Whilst this resolution is not as high as for CORONA images, it is comparable to that of Landsat MSS (79 m), and is generally sufficient for detecting many glacier changes. A more significant limitation with the ARGON data is that the images suffer from substantial distortion, especially towards the edges. This is the result of a number of factors, most notably the Earth's curvature over such large frames (see Figure 3.2), as well as the wide camera angle, film distortion, relief displacement and atmospheric refraction (Zhou *et al*., 2002).

Operating period	Nominal altitude (km)	Ground resolution (m)	Nominal ground cover of image (km)	Camera type	Film format (mm)	Film resolution (lp/mm)	Focal length (mm)
17/02/61-21/08/64	313	~138	556 x 556	Single frame	120 x 120	30	76

Table 3.5: Specifications of the ARGON KH-5 mapping system (Sohn and Kim, 2000; Zhou *et al.,* 2002).

Region	Date	Co-ordinates (bottom right)	Co-ordinates (top left)	Image ID
NW	29/08/2009	76 08 35 N, 061 41 58 W	79 41 14 N, 076 54 16 W	DS09058A028MC014
SW	21/08/2009	62 18 32 N, 042 11 15W	67 18 22 N, 055 01 11 W	DS09066A079MC040

Table 3.6: Details of ARGON images used in this study.

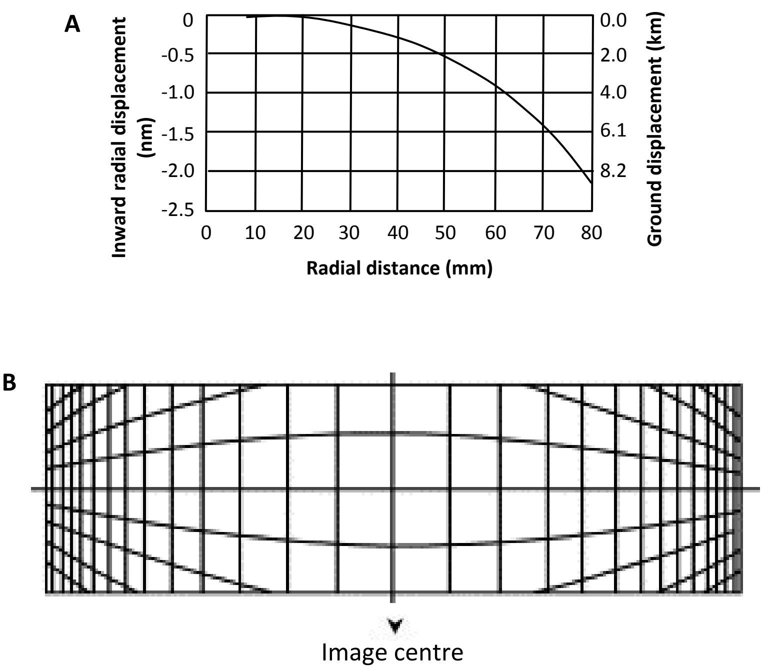


Figure 3.2: Illustration of scale of ARGON distortion: a) Effects of Earth's curvature on image (Zhou *et al.*, 2002: 1248); b) illustrated as a grid (Altmaier and Kany, 2002:225).

3.2.4 Aerial photographs

The first aerial photographs of Greenland were taken in 1931, although the first complete set of photographs was not taken until 1978. For this study, sets of photographs from 1953 (in the northwest), and 1943 (in the southwest), are used. The photographs are available to purchase from the Danish Ministry of the Environment (www.kms.de) and have excellent ground resolution of ~1 m^2, but a very small area footprint of ~8.5 by 8.5 km. To cover the whole of both study areas would require approximately 290 photographs and be very costly and time consuming to process. For this reason, only 11 glaciers from each region were mapped using aerial photographs, to give some insights into the early changes of a selected sample of glaciers.

3.3 Data processing

When attempting to analyse changes in surface features from different types of imagery at different time steps, it is important to spatially correlate all images to as high a degree as possible. This will ensure that any changes observed in glacier terminus position over time can be confidently assumed to reflect genuine fluctuations, rather than being an artefact of image mismatching. The first task in this study, therefore, was to orthorectify all images used, a process that encompasses three steps:

1. **Rectification:** features are fixed to their correct position on earth.
2. **Reprojection:** the image is transformed to a common co-ordinate system, such as Universal Transverse Mercator (UTM).
3. **Registration:** the same features in multiple images are matched exactly to one another.

Ideally, rectification and reprojection would automatically produce co-registered images, but in practice it was found that every image used needed fine tuning to some degree to improve the fit. The techniques used and difficulties encountered when orthorectifying each type of imagery are outlined below. All image processing and mapping tasks were performed using the ERDAS IMAGINE 9.3 software package, unless otherwise stated.

3.3.1 Processing Landsat

The majority of mapping was carried out using Landsat images, so it was decided to select one set as the base images for each area and orthorectify all other images to match these. The sets used are from 1999 in the northwest (Landsat TM) and 2001 in the southwest (Landsat ETM+), which were chosen because they cover the whole study area, have high spatial resolution (15-30 m) and are largely free from cloud and snow cover, so surface features are clearly visible. All Landsat images have already been rectified and transformed into the UTM WGS 84 projection by the USGS, so only registration to the base scenes was required. This was performed by placing ground control points (GCPs) on features that were visible in both the image being rectified and the base scene. Ideally, clearly defined and immoveable points or junction features, such as roads or buildings, would be used as control points. However, in the absence of man-made features in most of the images (a US airbase in the northwest being the exception), small ponds and islands were the preferred locations. Care was taken to ensure that features had not changed in size or shape over time, with images generally zoomed in to the pixel level to allow GCPs to be placed with precision. Ponds or lakes that were fed or drained by glacier meltwater streams or rivers were not used, as these are likely to have changed shape over time. For the older Landsat MSS images, which have a resolution of 79 m, identifying identical pixels was impossible but careful selection of features enabled the placing of points to a high level of precision (see Figure 3.3).

For each image, a minimum of 15 GCPs was used for the final transformation if only small registration adjustments were required, with over 30 GCPs used to register images that were poorly matched to begin with (Li *et al*., 1998; Sidjak and Wheate, 1999; Paul and Andreassen, 2009). The final selection of GCPs to be used in the transformation was determined by identifying large numbers of control points and deleting those that appeared to be least accurate. Generally, these were the points with the highest root mean square error (RMSE). Care was taken, however, to ensure that GCPs remained randomly distributed throughout the whole image. Images were transformed using a nearest neighbour sampling method with second order polynomial, due to the moderate variations in relief (Mather, 1999; Zhou *et al.*, 2002). Accuracy was primarily assessed using the RMSE of the control points, and was kept to a maximum of one pixel (30 m), often <0.5 pixels (15 m), for Landsat TM and ETM$^+$ images. This is the level of accuracy recommended by most previous studies (e.g. Li *et al*., 1998; Hall *et al*., 2003; Tsutomu and Gombo, 2007). Due to their coarser resolution, Landsat MSS images had a slightly higher error of 1-2 pixels (<60 m). Registration accuracy was also assessed using the GCP prediction tool in IMAGINE. Once several pairs of GCPs have been located manually in each image, the program attempts to predict the second point of all future pairs based on those already placed. Poor prediction indicates either that some of the points are wrong, or that not enough points have been identified for an accurate transformation. The final check on registration accuracy was performed after transformation, when the registered image was laid over the base image and 'swiped' across it to see if they matched in all areas, as illustrated in Figure 3.3.

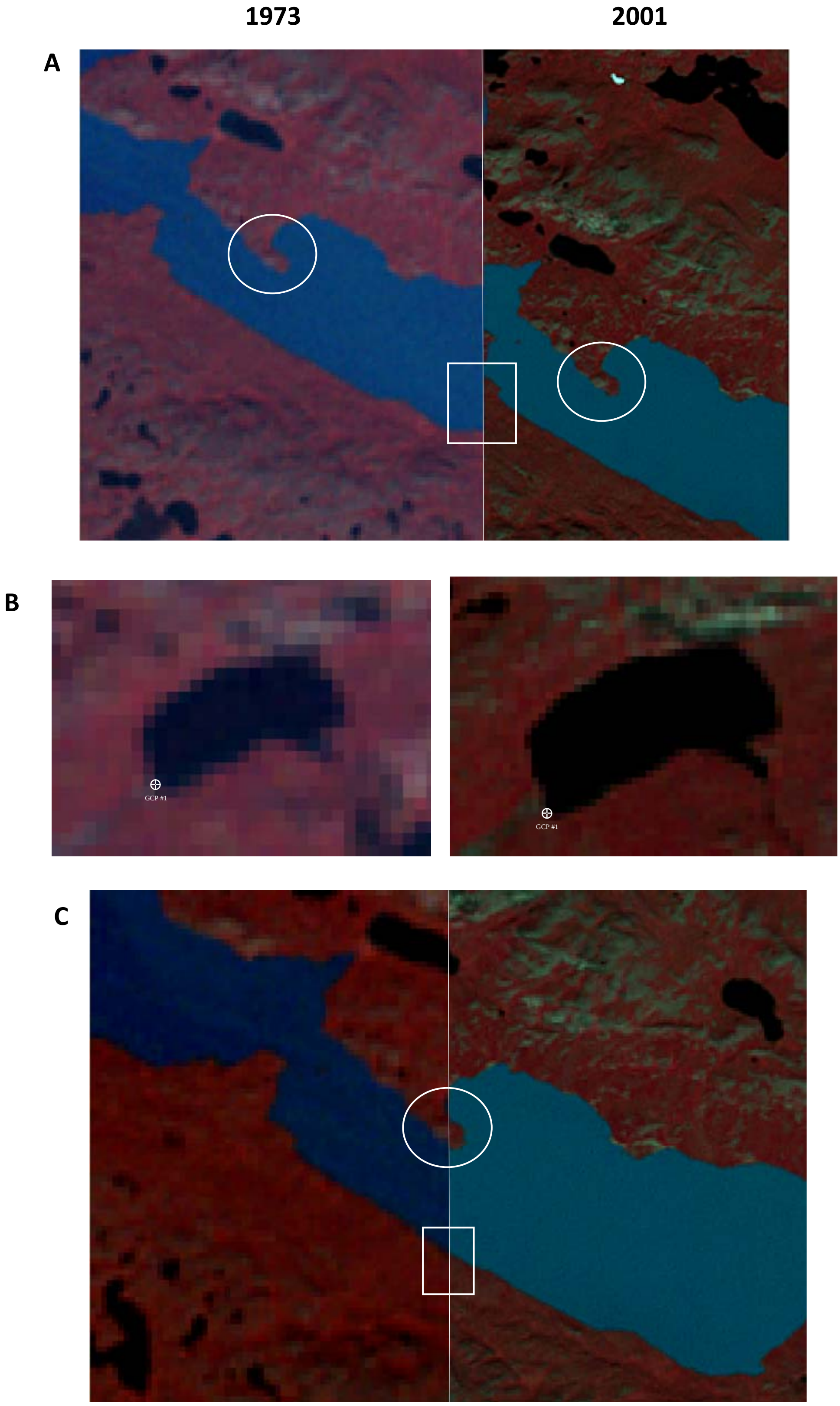


Figure 3.3: Images from southwest Greenland, illustrating the process of co-registering a 1973 Landsat MSS image to the 2001 Landsat ETM^{+} base image. a) The two images overlain before registration, with horizontal (circles) and vertical (rectangle) mismatch highlighted. b) A pond is identified in both images, and GCPs placed at the corner. c) The transformed 1973 image overlying the base image.

3.3.2 Processing ASTER

The ASTER scenes have been geo-rectified by NASA before distribution but are aligned to the path of the satellite rather than the north so must be reprojected to UTM WGS 84. This was done using a cubic convolution transformation. Following reprojection, each scene was registered to the Landsat base images using GCPs, as outlined above. ASTER scenes do not cover such a large area as Landsat, so in some cases it was possible to register them using fewer than 15 GCPs. However, due to many images having extensive snow or shadow obscuring their features, more GCPs were generally used to ensure an accurate transformation. The RMSE of re-projections ranged from 0.5-1 Landsat pixels (15-30 m).

3.3.3 Processing ARGON

ARGON images are delivered as digital scans of photographic prints, so have not been rectified or projected into a co-ordinate system. The first task was to crop each image to leave only the study area in the centre, because the edges generally suffer from greater distortion. The ARGON images were then registered to the Landsat base images. Because the ARGON images covered an area equivalent to approximately three Landsat images and were poorly matched to the base scene, over 100 GCPs were initially identified. Points that appeared to be inaccurately positioned were then removed, leaving ~80 GCPs for the final transformations. In order to correct the more substantial distortion of ARGON images the nearest neighbour transformation was performed with a third order polynomial. Due to the poor quality and low resolution of the ARGON images, it was difficult to register them as accurately as some other types of image, but error was kept to a maximum of 2 Landsat pixels ($60m^2$).

3.3.4 Processing aerial photographs

Aerial photographs were delivered as digital scans of the original photographic prints, without having been rectified or projected into a co-ordinate system, so were processed in a very similar way to the ARGON images. The images were first cropped to remove the photograph frames, then rectified to the Landsat base scenes. Because the aerial photographs cover a very small area, a minimum of just 6 GCPs was found to be adequate for accurate rectification. The images were transformed using nearest neighbour re-sampling, with a first order polynomial. Four out of the twenty-two photographs could not be rectified either because only small areas of land were included in the image, or because not enough features could be identified on both the photograph and Landsat scene. However, in all instances it was possible to map the approximate position of the terminus based on obvious landmarks, such as the shape of the coastline. For the rectified images, registration error was kept to maximum of one Landsat pixel (<30 m).

3.4 Data acquisition

3.4.1 Selecting glacier samples

Glaciers to be mapped were first selected for the southwest study region, with the aid of the glacier inventory compiled by Weidick *et al.* (1992). According to their database, this area of southwest Greenland has 1667 glaciers in total, including all ice sheet outlets and independent glaciers. There are data on location, size, class and many other characteristics for 1529 glaciers, and out of these, 1047 glaciers (68.5%) have an area of 1 km^2 or less. These glaciers were excluded from the potential sample as they are difficult to map accurately, and any changes in length are likely to be so small that they will be outweighed by the error of measurement (Yde and Knudsen, 2007). In addition, it can be hard to determine if such small glaciers are permanent features or semi-perennial snow patches (Weidick *et al.*, 1992). Excluding these glaciers gives a potential sample size of 482. To enable meaningful comparisons between ice sheet, ice cap and mountain glacier change, 60 mountain/ valley glaciers that were situated over 70 km from both the ice sheet and ice caps were excluded. This left a total of 422 glaciers of a suitable size and location for mapping. Attempts were then made to map as many of these glaciers as possible from the 2001 Landsat base image mosaic. During this process, many more glaciers had to be excluded from the dataset, mainly due to their having no obvious or only a poorly defined terminus. Since this study aims to assess advance and retreat on the basis of centreline length change, it was decided to ignore glaciers without an easily identifiable centreline. In addition, a small number of glaciers were excluded for having a heavily debris-covered terminus or being impossible to distinguish from surrounding snow. In total, 146 out of the 422 glaciers were mapped (34.6%). These glaciers are spread throughout the whole study area, and include a range of classes and terminus types (see Section 3.5.3 below for details). This sample is therefore considered suitably representative of the study area as a whole.

Following the selection of the outlet glaciers, a number of stretches of ice cap and ice sheet margin were selected for mapping. These were chosen using similar criteria to the outlet glaciers, in that they must be mostly free from debris cover and easily distinguished from any surrounding snow. In addition, the sample had to include examples of both ice cap and ice sheet margin. Based on these requirements, 18 sections of ice cap and ice sheet margin were mapped. These ranged in length from 2.1 - 34.4 km and covered a total length of 266 km.

A glacier inventory for the northwest study area does not yet exist. However, since the study area is a similar size to the southwest, it was decided to map a similar number of glaciers. Glaciers were mapped using the same criteria as in the southwest, by excluding any that appeared to be smaller than 1 km^2; without an obvious terminus and centreline; with an extensively debris-covered terminus; or that were indistinguishable from snow. In total, 118 glaciers of various classes and terminus environments were mapped, covering the whole study area. Based on visual scrutiny of the base image, this sample appears to include a high percentage of all glaciers in this area. Having selected the outlet glaciers to be mapped, some suitable stretches of ice sheet and ice cap margin were identified for analysis. In total, 39 margins were mapped, including some whole icefields, and sections of the ice caps and ice sheet. They ranged in length from 1.1 - 177 km, and had a total length of 872 km. Appendix A contains maps showing the location of all glaciers in each study area, whilst Appendix B contains tables summarising glacier characteristics and available data.

3.4.2 Mapping glacier termini

Previous studies have advocated the use of semi-automated techniques for mapping glacier area, most notably supervised classification from a thresholded band ratio image (Hall *et al*., 1989; Sidjak and Wheate, 1999; Paul *et al*., 2002). Many have derived good results from this method, which has the advantage of allowing large areas to be mapped quickly, easily and very precisely (Paul *et al*., 2002). However, this technique performs badly when attempting to classify glaciers that are partially obscured by snow, shadow or debris cover. For these glaciers, manual delineation by an experienced operator is recommended (Paul *et al*., 2002; Bolch *et al*., 2008). In both the northwest and southwest regions studied here, many glaciers are observed to have some debris cover at their terminus, or to be partially in shadow due to the mountainous terrain. It is likely, therefore, that semi-automated mapping results would have many errors, which would have to be corrected manually. This problem would be worse for the older Landsat MSS images, many of which were taken early in the year and thus have significant snow cover. In addition, it would be impossible to apply this technique to the ARGON images and aerial photographs, which are in black and white. For these reasons, manual delineation is considered to be the most accurate and appropriate mapping technique for this project.

Previous studies that have used manual delineation recommend mapping glaciers from a Landsat TM/ETM$^+$ false colour composite of bands 5, 4 and 3, to highlight the differences between ice and snow, and debris cover and moraines (Paul *et al*., 2002; Stokes *et al*., 2006). Visual comparison of a 2001 TM 4, 3, 2 and TM 5, 4, 3 image for the southwest study area confirmed that TM 5, 4, 3 is a better combination from which to map (Figure 3.4). Landsat MSS images do not have band 3 with the same spectral resolution as Landsat TM (see Table 3.2), so were mapped using a band 7, 5, 4 combination. ASTER images only have three bands with visible wavelengths (see Section 3.2.2), and ARGON images and aerial photographs are black and white, so these images were mapped as they came. All glaciers were mapped using the ERDAS IMAGINE 9.3 software program. Images were generally viewed at a scale of 1: 8000 (aerial photographs), 1: 15 000 (Landsat TM/ETM$^+$ and ASTER), 1:30 000 (Landsat MSS) or 1: 80 000 (ARGON), although in some instances images were viewed at higher or lower spatial resolution to aid terminus mapping. Glacier termini and ice margins were outlined manually, and the data stored as shapefiles.

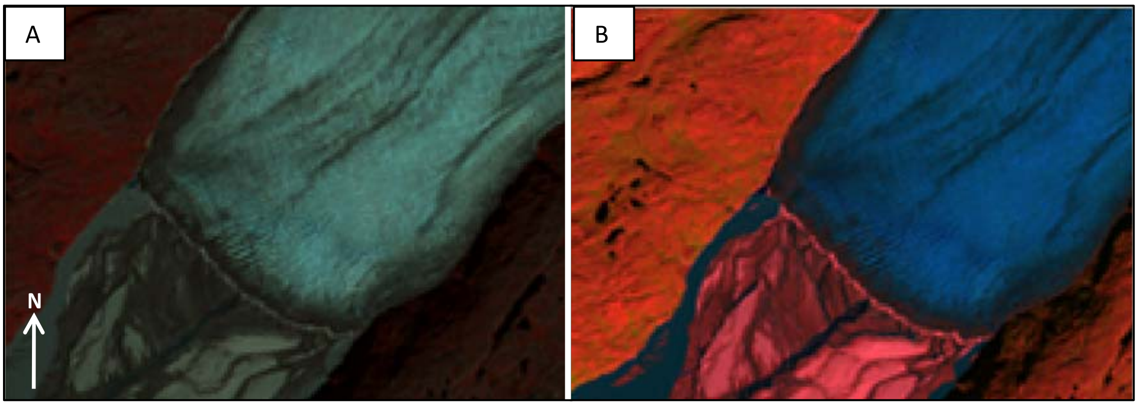


Figure 3.4: A southwest glacier terminus displayed as: a) a Landsat TM 4, 3, 2 (red, green, blue) image; and b) a Landsat TM 5, 3, 2 (red, green, blue) image, both at 1:15 000 scale.

In addition to mapping glacier terminus positions from the imagery listed above, the maximum extent of many glaciers during the Little Ice Age (LIA) was estimated by mapping the obvious terminal moraines from this period. In the case of marine-terminating (tidewater) glaciers this was impossible, so the position of the latero-frontal moraines was used to give an estimate of minimum LIA extent (Figure 3.5). In the southwest, several different dates for the maximum glacier extent during the LIA have been suggested, based on lichenometry and historical records, and ranging from 1800 to 1900 AD (Kelly and Lowell, 2009; see Chapter 2, Section 2.3.1). For the purposes of this study, the most commonly cited date of 1890 AD is used as the best approximation of age (Beschel and Weidick, 1973; Weidick, 1968). No detailed investigation has been done into the date of the LIA maximum extent in the northwest, but investigations of some individual glaciers in Northern Greenland suggest that maximum extent occurred in, or slightly before, 1900 AD (Davies and Krinsley, 1962). For this analysis, therefore, the date of 1890 AD is also used for moraines in the northwest. This date is at best only an approximation of maximum extent, with the exact timing probably varying within each region. However, it does still allow useful comparisons to be made between the two study areas.

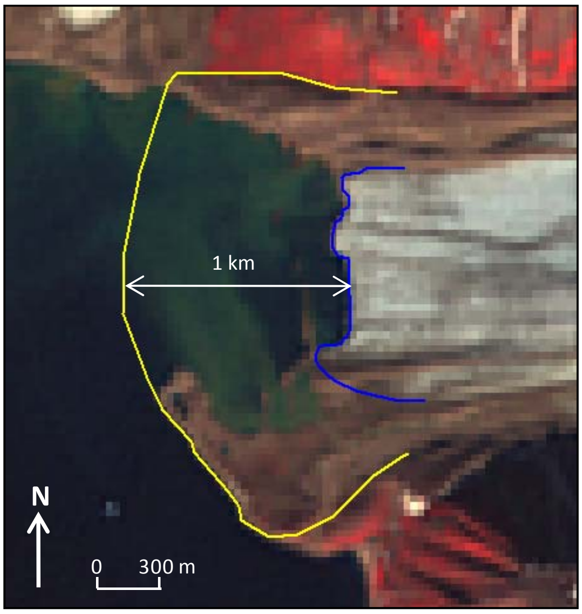


Figure 3.5: Glacier number 115 in the northwest study area, showing the terminus position in the LIA (yellow line, extrapolated from the latero-frontal moraine) and 1999 (blue line). Background image is Landsat ETM+ from the 24th of July 1999, displayed using bands 4-3-2 (red, green, blue).

3.5 Data analysis

3.5.1 Calculating glacier retreat

Two principal methods for quantifying glacier change from manually delineated terminus positions are described in the published literature. These are to calculate glacier length change from area change (e.g. Bolch *et al.*, 2008; Moon and Joughin, 2008), and to directly measure length change along the centreline (e.g. Stokes *et al.*, 2006). Moon and Joughin (2008:2) describe the process of deriving length change from area change in detail. They used an open-ended box to approximately delineate the sides of the glacier, then divided area change within the box by its mean width to estimate the length change (see Figure 3.6). The benefit of using this method instead of one single length measurement is that it takes into account uneven change across the glacier front (Moon and Joughin, 2008). However, Moon and Joughin (2008) principally used this technique to assess changes of tidewater glaciers, which are typically constrained by the edges of a fjord, so experience very little mass loss at the edges. In contrast, land-terminating glaciers often spread out to form piedmont lobes, with mass loss occurring around the whole terminus. This means that when area change occurs in a long thin crescent shape, rather than an approximate box shape, determining its width accurately is very difficult. Mean glacier width will give too small a number, so retreat will appear higher than is actually the case, whereas measuring around the terminus as a proxy for width may give too large a result, and thus low retreat. This is because the length will depend on where the cut-off point for area change measurements is placed. If the cut-off point is too far back down the terminus, where minimal change has occurred, then the long length will lead to very low estimates of advance or retreat distance. In addition, it is difficult to compare glaciers using this technique, as placing the cut-off point further back on one glacier could make it appear as though it has not retreated as much as its neighbour.

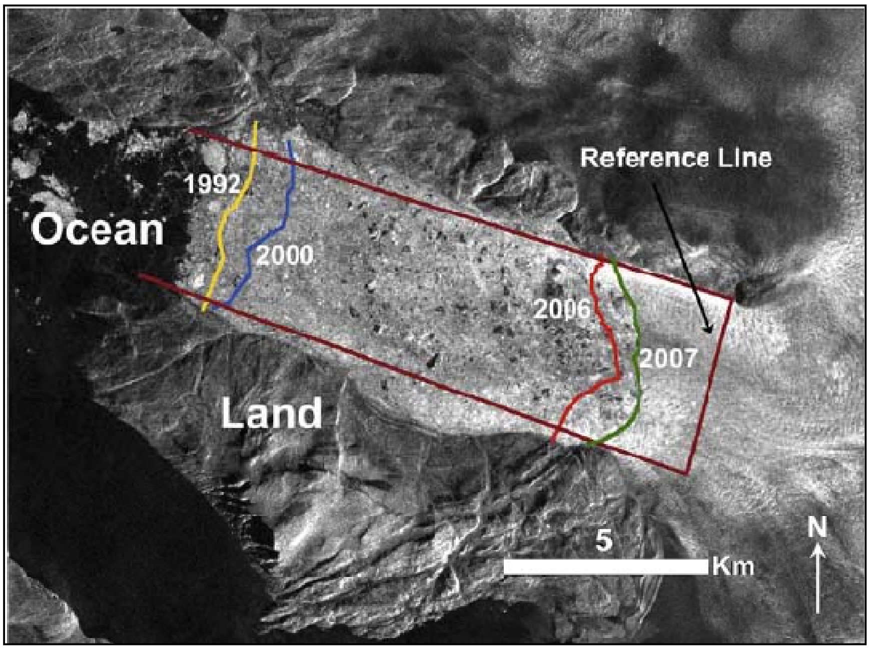


Figure 3.6: A digitised tidewater outlet glacier, illustrating the method of calculating glacier length change based on area change. The dark red lines delineate the approximate glacier margins and an arbitrary upstream reference line. The red, blue, green and yellow lines mark the terminus position at different time steps (from Moon and Joughin, 2008: 4).

Because the present study includes a wide range of glacier types, with very different terminus forms and terminus environments, calculating the length change from area is likely to be very time consuming and produce too many errors. Instead, the technique of manually measuring length change along the centreline will be used. The centreline is the recommended location for taking measurements, as it simple to identify and tends to coincide with the location of greatest advance/retreat, so will give an estimate of maximum length change (Stokes *et al*., 2006). It would also be possible to calculate mean retreat based on a series of measurements made around the glacier terminus, however this technique suffers the same limitations as calculations of area change: namely, that the decision of where to take measurements can severely impact upon the results. Measuring the centreline is not a completely error-free technique of course, as the decision as to where to position the centreline will affect the results (Hall *et al*., 2003). To minimise the effects of this as much as possible, the centreline was located on the base image and marked with a point before viewing the terminus positions for other years. All measurements between years were then made along this line of flow. This prevents the mapper from being tempted to place the centreline at a point that ‘looks interesting’. In the case of the ice cap and ice sheet margins, which do not have a centreline, length change was instead measured at a number of points and the mean calculated. A minimum of five measurements were taken along each stretch of margin, with 15 measurements made along the longest margin (IS001, in the northwest). As with the centrelines, the locations where measurements were to be made were first marked with points on the base image at approximately equal distances along the margin. All centreline measurements were made by zooming into a scale of 1: 3000, to allow the ends of the line to be placed exactly on the lines marking terminus position.

3.5.2 Estimating original glacier length

Absolute glacier advance/retreat is known to scale with overall glacier length; i.e. longer glaciers are likely to fluctuate over greater distances than smaller glaciers (Stokes *et al*., 2006; Jiskoot *et al*., 2009). In order to remove this bias when comparing glaciers of different sizes, this study will investigate relative retreat, as a percentage of total glacier length. Published data on glacier lengths are not available for either the northwest or the southwest study areas, so must be derived from satellite imagery and drainage basin data. Here, a combination of a digital elevation model (DEM), the Landsat base images and maps of drainage basin divides published by Weidick *et al.* (1992) are used to determine overall length.

The recently released ASTER global digital elevation model (GDEM) was used to create 3D maps of each study area. GDEM was developed by NASA and METI and is based on ASTER scenes, like those described in Section 3.2.2. All available images for each point on the Earth's surface have been processed and merged together to create a seamless DEM covering the whole world between 83° north and south. ASTER GDEM is the only widely available DEM to have a high spatial resolution, universal coverage and to be suitable for use at high latitudes and in mountainous terrain (ERSDAC, 2009). It can be downloaded as individual tiles 1° lat/long in size (3601 x 3601 pixels) from the NASA Warehouse Inventory Search Tool (https://wist.echo.nasa.gov). The horizontal and vertical spatial resolution is 30 m, with a standard deviation of 7-14 m. This is adequate for the purposes of this study.

DEM analysis was undertaken using the software programs ArcMap and ArcScene, part of ArcGIS 9.3. The individual tiles covering each study area were downloaded, converted from TIFF to GRID format, and mosaicked together to form two seamless DEMs. These comprised 18 tiles in the southwest, and 26 tiles in the northwest. Using these DEMs, attempts were first made to calculate the size of individual drainage basins in each region, but due to the size and complexity of the study areas the resulting basin delineations lacked both detail and accuracy. Instead, glacier lengths were measured from contour maps of each region. Two contour maps, of 100 m and 50 m intervals, were originally created from the southwest DEM in ArcMap. The 50 m contours did not give much more detail than the 100 m contours for the centres of ice caps, and were much noisier and harder to interpret in the steeper terrain near the terminus. It was therefore decided to measure glacier lengths based on the 100 m contour map.

When the Landsat base images were overlain on the DEMs, a visual comparison indicated a close fit, with a horizontal mismatch of only a couple of pixels (~60 m). Since the majority of glaciers to be measured are 1 km or longer this error will not make a significant difference, so registration was not considered necessary. Glacier lengths were mapped onto the Landsat base images, which had the contour maps laid over them. Decisions regarding where to draw the lines, and how long they should be, were made with reference to the DEM and any surface topography/rock outcrops visible on the Landsat image. The position of the terminus at the earliest available time period was used as the starting point for each glacier (for example, the LIA moraine), and the length was measured back to the approximate location of the drainage basin divide (see Figure 3.7). These were identified as being the point of highest elevation in a local area. To assess the accuracy of this technique, 52 glacier lengths were mapped using the southwest DEM, and then compared to the maps of drainage basin area given in Weidick *et al.* (1992). Only 5 out of the 52 glaciers (9.6%) had significant errors in mapping. In the northwest study area it was not possible to check the accuracy of mapped glacier lengths, but it is likely that errors are no greater than those for the southwest.

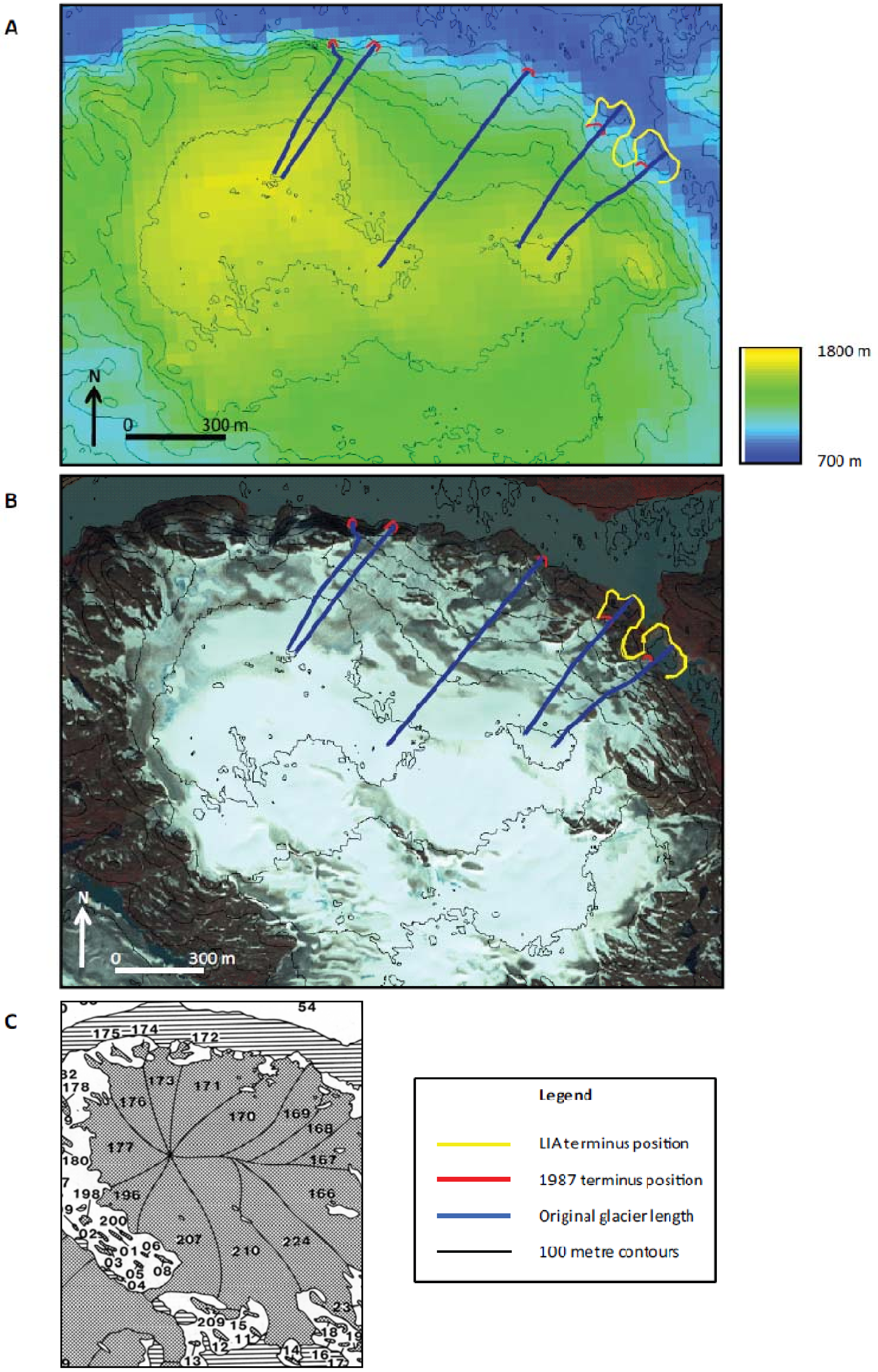


Figure 3.7: Images of an ice cap in the southwest study area, illustrating the process of determining original glacier length using: a) a DEM with 100 m contour intervals; b) the Landsat 2001 ETM+ base image, with 100 m contours; and c) a map of drainage divides from Weidick *et al*. (1992: 150).

3.5.3 Classifying glaciers

One of the objectives of this study is to examine the impact that primary classification (class) and terminus environment have upon rates of glacier retreat. In order to fulfil this objective, the class and terminus environment of every glacier mapped must be identified. The most up-to-date descriptions published by the World Glacier Monitoring Service (WGMS, 2008b) were used to do this for glacier class. For terminus environment, glaciers were divided into lake, land, land/lake and tidewater categories based on visual inspection of the Landsat images. Detailed descriptions of class and terminus categories are given in Tables 3.7 and 3.8.

Terminus environment	**Description**
Lake	Whole width of terminus is calving into a lake
Land	Whole of terminus terminates on land. Any meltwater lakes are very small and temporary.
Land/lake	Part of terminus is calving into a lake whilst part terminates on dry land. Lake is a permanent feature.
Tidewater	Glacier calves into the sea or fjord. Can be grounded or floating.

Table 3.7: Descriptions used to identify glacier terminus environment.

Primary classification (class)	Description	Any measured in the northwest?	Any measured in the southwest?
Miscellaneous	Any type not listed below	N	N
Continental ice sheet	Inundates areas of continental size	Y	Y
Icefield	Ice mass of sheet or blanket type, of a thickness that is insufficient to obscure the subsurface topography	Y	N
Ice cap	Dome-shaped ice masses with a radial flow	Y	Y
Outlet glacier	Drains an ice sheet, icefield or ice cap, usually of valley glacier form; the catchment area may not be easily defined	Y (Divided into ice sheet, icefield and ice cap outlets)	Y (Divided into ice sheet and ice cap outlets)
Valley glacier	Flows down a valley; the catchment area is well defined	Y	Y
Mountain glacier	Cirque, niche or crater type, hanging glacier; includes ice aprons and small groups of units	Y	Y
Glacieret/ snowfield	Small ice masses of indefinite shape in hollows, river beds and on protected slopes. Have developed from snow drifting, avalanching and/or particularly heavy accumulation in certain years; usually no marked flow pattern visible; exists for at least two consecutive years	N	N
Ice shelf	Floating ice sheet of considerable thickness attached to a coast nourished by a glacier(s); snow accumulation on its surface or bottom freezing	N	N
Rock glacier	Lava-stream-like debris mass containing ice in several possible forms and moving slowly downslope	N	N

Table 3.8: Descriptions used to identify primary classification (class) of each glacier. Note that where the ice sheet, icefields and ice caps have been marked as being mapped, this refers to sections of margin. Descriptions taken directly from WGMS (2008b: 99).

3.5.4 Identifying surge-type glaciers

Surge-type glaciers can exhibit a range of behaviours, but are broadly defined as undergoing cyclical fluctuations in velocity (Copland *et al*., 2003; Grant *et al*., 2009). This consists of a short active phase, during which glacier velocity increases significantly and the terminus generally advances rapidly, and a longer quiescent phase, characterised by thinning at the terminus, accumulation at the head and relatively small variations in terminus position (Copland *et al.*, 2003; Yde and Knudsen, 2007). Identification of possible surge-type glaciers is important when investigating the links between glacier fluctuations and climate and other controlling factors, as the timing of the advance and retreat cycles usually occurs independently of climate forcing (Yde and Knudsen, 2007).

Surge-type glaciers are widespread throughout the Arctic (Grant *et al*., 2009), and several have been reported in the Central West and Central East regions of Greenland (Weidick, 1984; Weidick, 1995; Yde and Knudsen, 2007). The only surge type glacier previously identified in the northwest study area is Harald Moltke Brae, which was observed to have actively surged from 1926-1928, 1937-1938, c. 1956 and c. 2005 (Mock, 1966; Rignot and Kanagaratnam, 2006). No surging glaciers have been reported in the southwest study area. Whilst Harald Moltke Brae was mapped as part of this study, the results were excluded from all general analyses of glacier fluctuations and presented in a separate section. All glaciers in each study area were examined after mapping, to identify any other potential surge type glaciers. Copland *et al.* (2003) published a list of glaciological criteria that are indicative of surging, which are summarised by Grant *et al*. (2009) in Table 3.9. Glaciers can be classified in one of four categories (Copland *et al*., 2003: 77):

1. **Confirmed surge**: active surge phase is observed, and glacier has many distinct surge features.
2. **Likely to have surged**: active phase not observed, but glacier has many distinct surge features.
3. **Possibly surged**: active phase not observed, and only a few surge features present.
4. **Non-surge**: no active phase or surge features observed.

Glaciological criteria	Description
Looped moraines	Produced when medial moraines are deformed due to the combination of fast- and slow-flowing ice within adjacent glaciers
Deformed ice structures	Form in a similar manner to looped moraines
Shear margins on glacier surface	Develop at the boundary between fast- and slow-flowing ice
Heavy surface crevassing	Indicative of the active phase of the surge cycle and develop due to increased longitudinal stresses
High surface velocities	Occur during the surge phase
Rapid advance of glacier terminus	Indicative of the active phase of the surge cycle
Highly digitate tidewater terminus	Terminus is splayed into lobes by longitudinal crevasses
Strandlines of ice	Formed on the adjacent valley sides due to rapid thinning of the upper part of the glacier
Surface potholes	Typically appear during the quiescent phase; they form in crevasses formed during the surge phase or in depressions between transverse ridges

Table 3.9: Glaciological criteria for identifying surge type glaciers (from Grant *et al.*, 2009: 962)

Based on the criteria listed in Table 3.9 all southwest glaciers were classified as non-surge, whilst in the northwest only Glacier 75 (Berlingske Brae) was identified as having possibly surged (in addition to Harald Moltke Brae). Glacier 75 is a tidewater terminating outlet glacier of the North Ice Cap, which was mapped at six time steps between 1953 and 2009. The mapping revealed that the glacier terminated on land during 1953 and 1964, but that it subsequently advanced by 1.58 km to terminate in the fjord in 1987 (Figure 3.8). This equates to an overall rate of advance of 69 m per year. Of the 42 glaciers in the northwest that were measured on both the 1964 and 1987 imagery, only Harald Moltke Brae advanced a greater distance (1.97 km) than Glacier 75. No other glacier measured had advanced more than 0.39 km overall. When relative rates of change were compared, Glacier 75 had advanced further as a percentage of its original length than any other glacier; +4.12 %, compared to <+2.33 %. Some meltwater ponds can also be observed on the surface of the glacier in the 2001 Landsat image, which can be indicative of crevasses formed during previous surge events (Copland *et al.*, 2003; Grant *et al.*, 2009). In addition, the glacier has a much longer terminus than most others that drain the North Ice Cap and icefields in this area, and this has often found to be characteristic of surge type glaciers (e.g. Clarke, 1991; Yde and Knudsen, 2007; Grant *et al.*, 2009). Based on this evidence, Glacier 75 is classified as having possibly surged, so is excluded from all general analyses of glacier fluctuations (unless otherwise stated), and analysed separately.

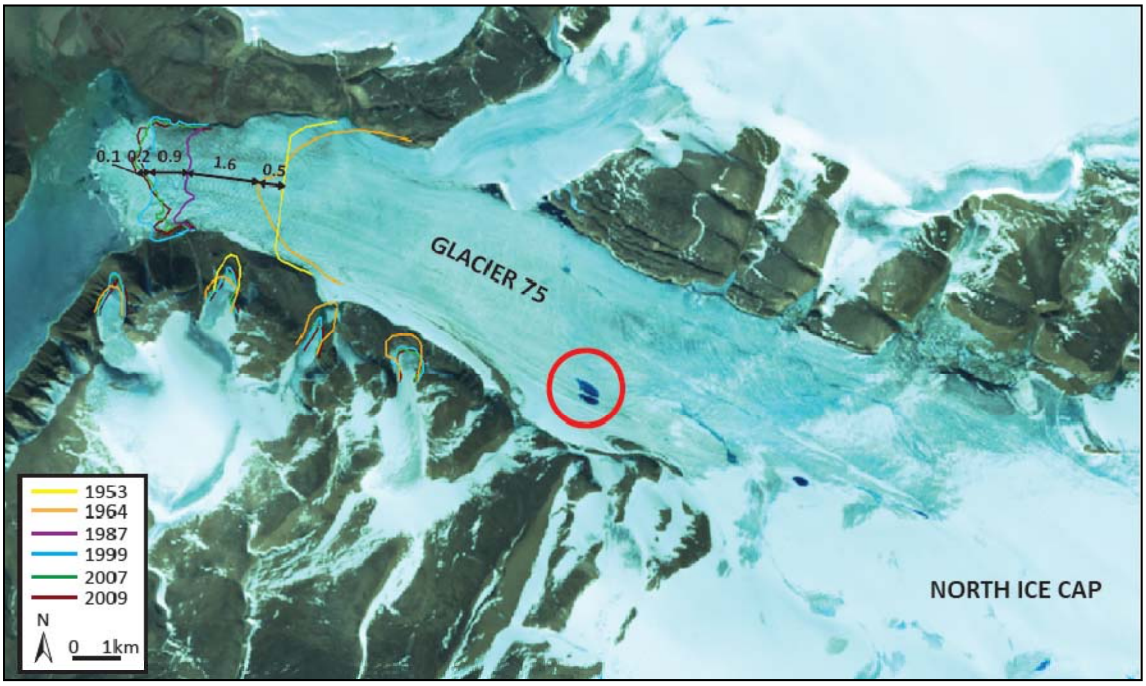


Figure 3.8: Terminus position of possible surge type Glacier 75 (Berlingske Brae) in the northwest study area mapped at six time steps between 1953 and 2009. The red circle highlights a surface meltwater pond. Underlying image is the 1999 Landsat TM base image, displayed as band 4,3,2 (red, green, blue) combination.

3.5.5 Statistical analysis of length changes

One-way analysis of variance (ANOVA) and Pearson's correlation coefficient tests are used to determine whether relationships between rate of length change and glacier characteristics are significant. These are parametric tests, so assume that the data has a Normal distribution. Normal density and histogram plots of rate change and original length data in each of the samples listed above show that not all have a perfect Normal distribution. A range of different transformations were applied to these data in an attempt to improve the distribution, including: an x-squared transformation (x^2), a square root transformation ($\sqrt{x}$), a log transformation ($\log_{10}(x)$), a cube root transformation ($x^{1/3}$) and a reciprocal transformation (1/x). Many of these transformations can only be carried out on positive values, so a value of two was added to all results to convert any negative results to positive, whilst maintaining the data spread. Examination of normal density and histogram plots after these transformations showed that none had significantly improved the distribution, so the un-transformed data are used throughout this chapter.

3.6 Error analysis

3.6.1 Sources of error

Five main sources of error affecting the relative glacier length change data have been identified, and these are the pixel resolution of the images used, co-registration errors between each image and the Landsat base scenes, accuracy of terminus delineation, accuracy of centreline change measurements, and accuracy of original length measurements. A summary of the pixel resolutions and estimated co-registration errors for each type of imagery is given in Table 3.10. For all terminus position measurements to be affected by the maximum registration error, the whole of each image would have to be displaced compared to the Landsat base scene. However, it is more likely that only parts of each image will be affected by the maximum error, with others being registered almost exactly to the base scene. Therefore, it is more realistic to cite co-registration error as being 50 % of the maximum displacement (Burgess and Sharp, 2004).

For relatively clean glacier termini, previous studies have found that terminus delineation error is generally no greater than the pixel size of the image being mapped (Burgess and Sharp, 2004; De Beer and Sharp, 2007). The majority of glaciers mapped in this study had relatively clean termini, so error is assumed to be no greater than the pixel resolution. This was confirmed by mapping three different glacier terminuss twenty times each from the 2001 Landsat ETM+ base scene, and then measuring the maximum distance between any two digitised terminus positions. This was found to be approximately 30 metres for all three glaciers, (including the two with partially debris covered terminuss), and thus matches the pixel size of the image. As stated previously, measurements of change in position were made by viewing the image at a high resolution so that the centreline could be placed precisely on the terminus outlines. Any error associated with these measurements is, therefore, so small that it can be disregarded. To calculate errors associated with measurements of original glacier length, three glaciers of different lengths were selected for testing. The original length of each glacier was digitised twenty times, and the maximum error in metres converted to a percentage of mean total length. Error was found to range between 5 and 6 % for all three glaciers, so ± 6 % is taken as the maximum general error for original lengths.

3.6.2 Calculating overall error

Previous studies (Hall et al., 2003; De Beer and Sharp, 2007) have calculated total error (E_T) for measurements of glacier terminus change using the following equation:

$$E_T = \sqrt{a^2 + b^2} + \sigma \qquad (\textit{Equation 1})$$

where a and b are the pixel resolution of each image, and σ is the co-registration error. For example, the total error for glacier length changes between 1964 and 2001 in the southwest study area is calculated from the pixel size (44 m) and 50 % of the registration error (60 m) of the 1964 ARGON image,and the pixel size of the 2001 Landsat ETM+ base image (30 m). This gives the equation:

$$E_T = \sqrt{44^2 + 30^2} + 30 \qquad (\textit{Equation 2})$$

which results in an estimated error of ±83 m for glacier length change measurements between 1964 and 2001 in the southwest study area. Table 3.10 details the errors calculated for each type of imagery compared to the Landsat base images. It must be remembered that these are estimates of the maximum error, and it is probable that terminus position errors for the majority of glaciers mapped will be lower than these figures.

Type of imagery	Pixel size (m^2)	Maximum co-registration error (m)	**Northwest** Total error compared to 1999 Landsat base scene (m)	**Southwest** Total error compared to 2001 Landsat base scene (m)
Aerial photographs	~1	30	45	45
ARGON	89 (NW) / 44 (SW)	60	124	83
Landsat MSS	79	60	114	114
Landsat TM / ETM+	30	30	57	57
ASTER	15	30	48	48

Table 3.10: The pixel size, maximum co-registration error and total errors calculated for each type of imagery when compared to the 1999/ 2001 Landsat TM/ ETM+ base images. Errors are calculated using Equation 1 above.

3.6.3 Impact of errors on length change measurements

All results in this study are reported as a rate of length change per year, with the majority converted to a percentage of overall glacier length. The glacier length changes have also been calculated for a variety of time periods, ranging from 2 to 74 years, and are based on a variety of image combinations (such as ARGON and Landsat MSS, or aerial photographs and ARGON). Therefore, the actual absolute error will vary depending on the time period studied, whilst the relative error (as a percentage of glacier length) will vary for each individual glacier within a sample. Mean absolute and relative length change errors are compared to mean glacier length change for several different time periods that form the basis of the analysis in Chapters 4 and 5 (Tables 3.11 – 3.14). To calculate the mean glacier length changes, all negative values were converted to positive so that advancing and retreating glaciers did not cancel each other out and give a mean length change of zero. Comparison of these results to the maximum error calculated for each time period indicate that both the absolute and relative changes in glacier length outweigh the estimated maximum error at virtually all time periods (see Tables 3.11-3.14). The size of the errors varies depending on the types of imagery used for mapping and length of time studied, and generally become more significant as the time period studied becomes shorter.

Time period	Number of years	Mean original glacier length (km)	Mean absolute length change (m a^{-1})	Mean relative length change (% a^{-1})	Absolute error (m a^{-1})	Relative error (% a^{-1})
LIA-1964	74	17.5	8.5	0.06	1.7	0.01
1964-1987	23	30.9	17.3	0.08	5.4	0.02
1987-1999	12	30.9	15.5	0.06	4.8	0.02
1999-2009	10	30.9	27.3	0.09	5.7	0.02

Table 3.11: Mean absolute and relative length changes compared to maximum calculated errors, for northwest glacier samples analysed in Chapters 4 and 5.

Time period	Number of years	Mean original glacier length (m)	Mean absolute length change (m a^{-1})	Mean relative length change (% a^{-1})	Absolute error (m a^{-1})	Relative error (% a^{-1})
LIA-1964	74	44.7	23.6	0.19	1.13	0.00
1964-1987	23	44.4	11.8	0.05	3.6	0.01
1987-2001	14	44.4	11.6	0.04	4.1	0.01
2001-2009	8	44.4	14.4	0.07	7.2	0.02

Table 3.12: Mean absolute and relative length changes compared to maximum calculated errors, for southwest glacier samples analysed in Chapters 4 and 5.

Time period	Number of years	Mean original glacier length (m)	Absolute length change (m a^{-1})	Relative length change (% a^{-1})	Absolute error (m a^{-1})	Relative error (% a^{-1})
1953 - 1964	11	28594	37.0	0.09	10.8	0.04
1964-1975	11	44.8	0.19	0.08	13.5	0.03
1975-1987	12	44.8	61.3	0.15	9.5	0.02
1987-1999	12	44.8	13.4	0.06	4.8	0.01
1999-2009	10	44.8	40.0	0.10	5.7	0.01
2007-2009	2	22.6	14.5	0.13	24.3	0.05

Table 3.13: Mean absolute and relative length changes compared to maximum calculated errors, for decadal northwest glacier samples analysed in Chapters 4 and 5.

Time period	Number of years	Mean original glacier length (m)	Mean absolute length change (m a^{-1})	Mean relative length change (% a^{-1})	Absolute error (m a^{-1})	Relative error (% a^{-1})
1943 -1964	21	33.1	21.3	0.33	3.5	0.01
1964-1973	9	40.9	21.9	0.14	16.5	0.04
1973-1987	14	40.9	11.1	0.06	8.2	0.02
1987-2001	14	40.9	8.2	0.04	4.1	0.01
2001-2009	8	40.9	10.0	0.09	6.1	0.01
2007-2009	2	48.9	66.0	0.25	24.3	0.05

Table 3.14: Mean absolute and relative length changes compared to maximum calculated errors, for decadal southwest glacier samples analysed in Chapters 4 and 5.

Chapter 4

Results I: Glacier fluctuations during the 20th century

4.1 Introduction

The following two chapters present the results of the glacier mapping outlined in Chapter 3, and use the data gathered to address the primary objectives of the study. These were: to compare patterns of glacier length change in the north and south; to examine differences in length change for different glacier classes; to investigate the influence of terminus environment and other variables on length change; and to assess links between length change and regional climate data (see Chapter 1 for more detail). This first results chapter focuses on overall glacier fluctuations throughout the 20th century. Length change data for all outlet glaciers are presented separately for both study areas over various time periods, to allow differences between the north and south to be examined (Section 4.2). A summary of the key findings is presented in Section 4.3. The second results chapter explores the influence that class, terminus environment, climate and other factors may have had on glacier length changes.

4.1.1 Summary of data collected

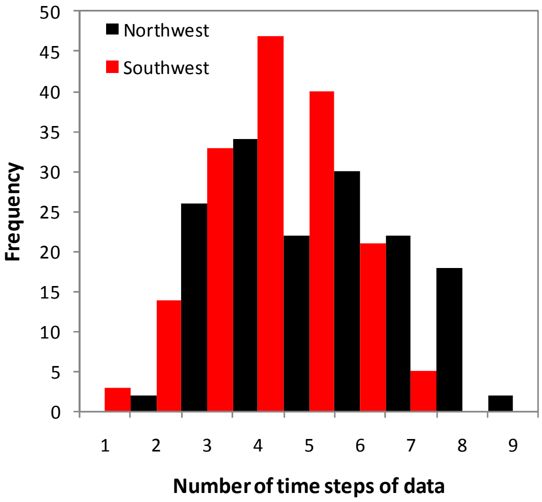
In total, 322 outlet glaciers and ice sheet/ice cap margins, comprising 157 glaciers in the northwest study area and 163 glaciers in the southwest, were mapped from aerial photographs and satellite imagery dating back to 1943. The position of many glaciers at the LIA maximum was also estimated based on terminal moraines (see Chapter 3, Section 3.4.2). Glaciers in the northwest were measured at 11 time steps between the LIA and 2009, whilst glaciers in the southwest were mapped at 10 time steps. Due to a lack of suitable images, it was found to be impossible to map every glacier at every time step; a summary of the number mapped at each year is presented in Table 4.1. The number of time steps at which individual glaciers were mapped varies from one to nine, with the majority having data at between three and seven time steps, over a range of 10-120 years (Figure 4.1). During the mapping process, it transpired that three glaciers in the southwest could only be mapped at one time step (2001). In addition, glacier numbers 59 (Harald Moltke Brae) and 75 (Berlingske Brae) in the northwest were observed to display evidence of surge-type behaviour (see Chapter 3, Section 3.5.4). These five glaciers were thus excluded from the dataset.

Throughout this chapter, the data are presented as relative rates of change per year to eliminate bias resulting from differences in glacier size, as longer glaciers are likely to retreat further than smaller glaciers in absolute terms, but this may only equate to a tiny proportion of their overall length (Stokes *et al.*, 2006; Jiskoot *et al.*, 2009). Where relevant, absolute retreat rates are presented alongside the relative rates for illustrative purposes. Relative change (in percent) is calculated by dividing absolute change (in metres) by the original glacier length and multiplying by one hundred. This number is converted to a rate of change per year by dividing it by the number of years between measurements. All results are presented separately for the northwest and southwest study areas. Throughout this results chapter, analysis is based on a minimum sample size of eight glaciers, and the actual numbers used are stated in figure captions.

Northwest	
Year	Number of glaciers mapped
LIA	72
1953	11
1964	67
1972	21
1975	42
1987	71
1995	35
1999	157
2002	85
2007	153
2009	127
Total	**157**

Southwest	
Year	Number of glaciers mapped
LIA	61
1943	11
1964	57
1973	40
1985	18
1987	133
1992	66
2001	163
2007	48
2009	103
Total	**163**

Table 4.1: The total number of glaciers and margins measured for each year of the study in the northwest and southwest study areas.



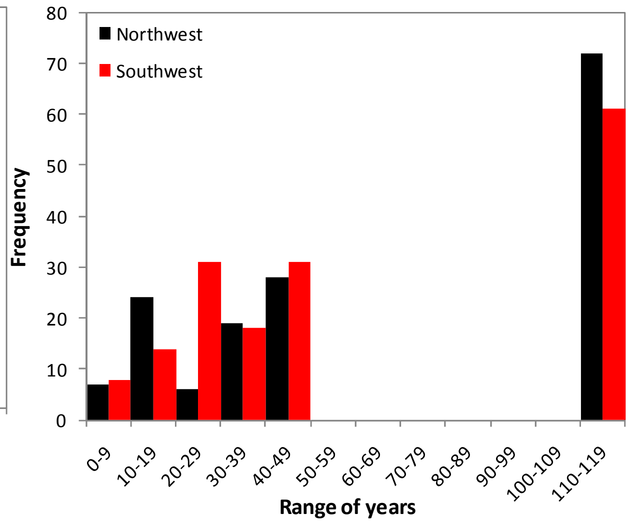


Figure 4.1: a) Summary of the frequency of glaciers with data for different numbers of time steps, and b) the number of glaciers with data spanning different lengths of time.

4.2 Rates of length change for all glaciers

In this section, variations in glacier length changes are examined for all types of glacier and comparisons made between the northwest and southwest study areas. Because most glaciers could only be measured at a few time steps, a balance between detailed temporal investigation of rate changes using small samples and broader overviews of change using large samples must be sought. In consequence, rate changes are assessed using several different sub-samples of the dataset in each of the sections 4.2 to 4.4. Firstly, general patterns of advance or retreat at three time steps over the whole time period from the LIA- 2009 are examined using the largest possible sample size. Rate changes are then scrutinised in increasing detail using smaller samples at four time steps, and decadal intervals. In addition, variations over the past decade are analysed more closely, along with any other decades where data is available at more time steps. A short summary of the key findings is presented at the end of each section.

4.2.1 An overview of rate changes from the LIA-2009

A broad overview of rate changes for each study area during the 20th century is obtained by comparing relative rates of retreat at three time intervals. Only 55 out 322 glaciers were measured at the LIA, 1964 and 2009, so the sample size was increased by using separate samples of all glaciers measured at each pair of time steps (LIA-1964, 1964-1999/2001, 1999/2001-2009). Table 4.2 gives a summary of the glacier samples, and the mean and individual retreat rates are shown in Figure 4.2. The results suggest that the distance retreated per year between the LIA and 2009 increased over time for the majority of glaciers in the northwest, whereas there has been no such overall increase in the southwest. Here, glaciers underwent the least retreat between 1964 and 2001, at only -0.01% a^{-1}. It is also interesting to note that the range of distances retreated by individual glaciers has increased over time in both study areas, but particularly in the northwest, where 8 glaciers retreated rapidly between 1999 and 2009. These glaciers are dispersed throughout the study area, but all are mountain and icefield glaciers or the margins of small ice caps/icefields.

When absolute retreat is examined (Figure 4.3), the glaciers that retreated the furthest distance are Glaciers 48 (Farquhar Gletscher) and 50 (Heilprin Gletscher) in the northwest and 1CH 23 003a (Kangiata nunata sermia) in the southwest. However, none of these glaciers were identified as retreating rapidly in Figure 4.2. This is because these three are all big tidewater outlet glaciers of the main ice sheet, so whilst they may have retreated several hundred metres per year this is only a tiny proportion of their overall lengths (estimated to be ~50 km). In contrast, the ice cap/icefield margins with the fastest relative retreat per year (OI016 and OI018) only retreated 16 and 24 metres per year respectively in absolute terms. However, because they are only 0.88 and 1.26 km long, this ice loss constitutes a much higher proportion of their overall length than that observed for the three tidewater outlets. These results highlight the importance of using relative rates of glacier length change to examine the retreat of different glaciers, as absolute length changes are strongly biased by glacier size. It should also be noted that the long time interval between measurements may mask significant fluctuations in rate, and that variation may be partially the result of using different sub-samples. However, the sample sizes are sufficiently large that the trends identified can be considered fairly representative of overall glacier behaviour in this region during the 20th century.

	Northwest			Southwest		
Time period	LIA-1964	1964-1999	1999-2009	LIA-1964	1964-2001	2001-2009
Number of glaciers	39	67	124	21	58	103
Mean original length (km)	17.5	23.2	16.6	44.7	39.8	33.9
Number of glaciers as a proportion of total dataset (%)	25	43	79	13	36	63

Table 4.2: Summary of glacier samples used for LIA to 2009 analysis in Figures 4.2 and 4.3.

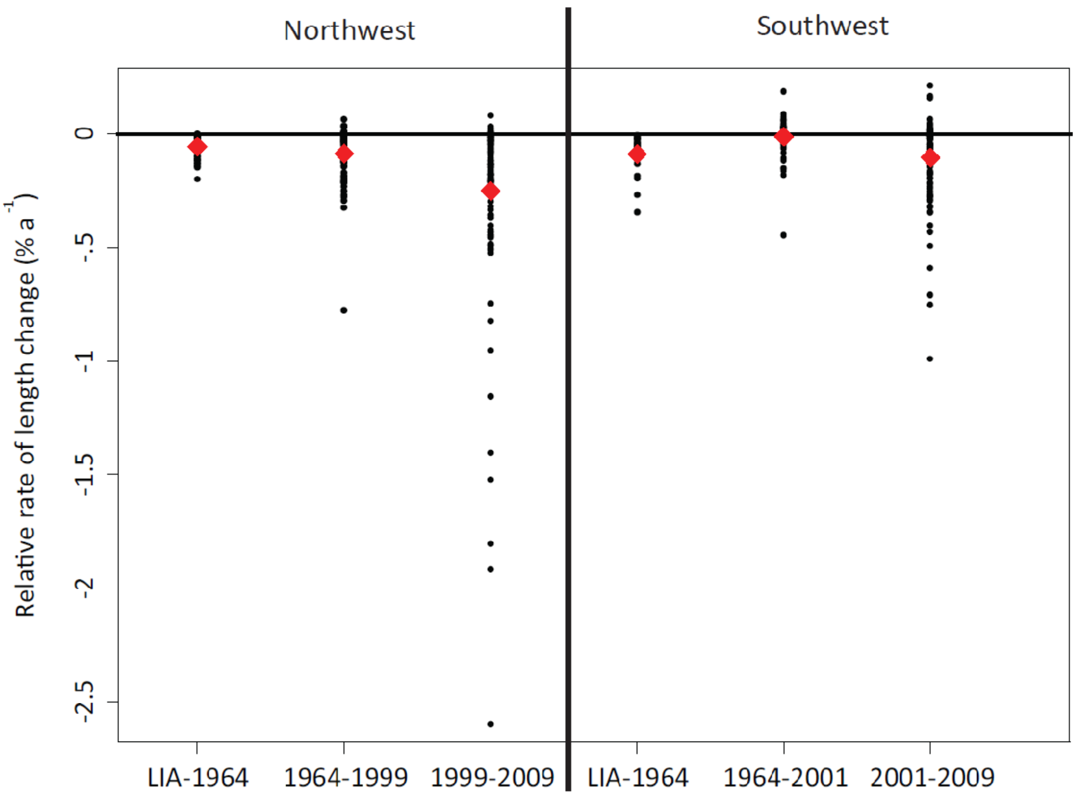


Figure 4.2: Mean (red dot) and individual annual relative rates of glacier length change calculated for three time steps between the LIA and 2009, using different sub-samples of the dataset (see Table 4.2 for details).

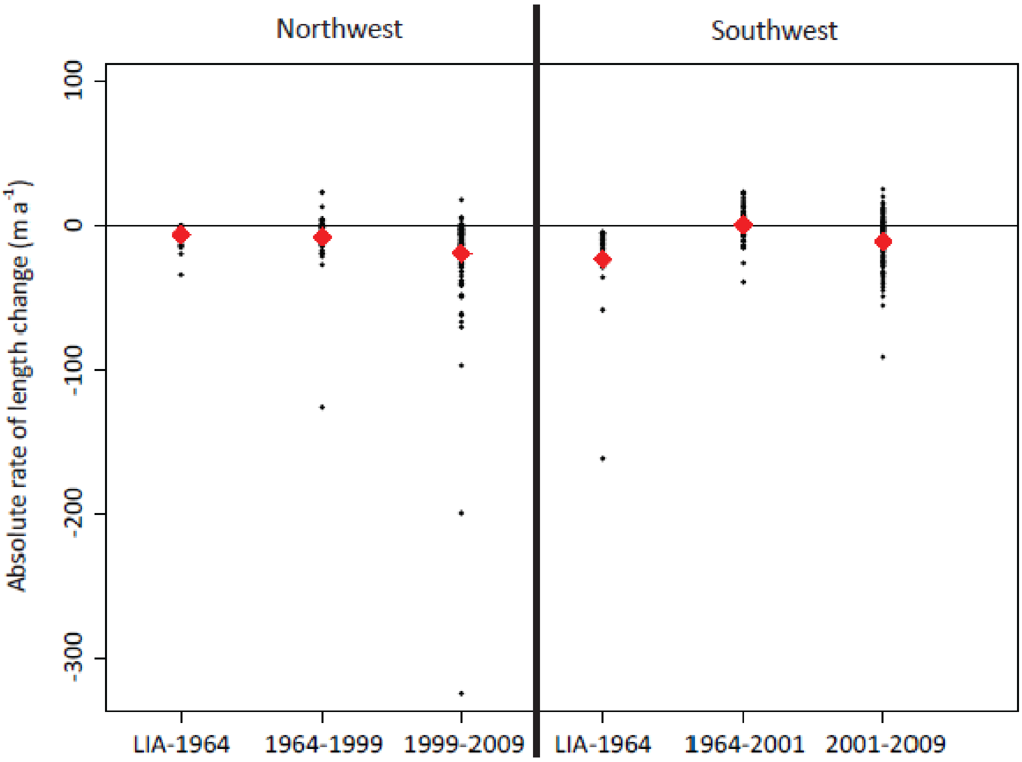


Figure 4.3: Mean and individual annual absolute rates of glacier length change of the glaciers shown in Figure 4.2, for the LIA to 2009.

4.2.2 Rate changes from 1964-2009

In order to examine rate changes in more detail, smaller samples of glaciers that were measured at 1964, 1987, 1999/2001 and 2009 are used (Figure 4.4). Measurements made at the LIA are excluded from this dataset, in order to maximise the sample size. The data suggest that in the northwest, glaciers retreated the greatest distances per year between 1999 and 2009. In the southwest, a steady increase in distance retreated each year was observed over the whole time period, from 0.01% a^{-1} advance from 1964-1987 to -0.06% a^{-1} retreat from 2001-2009. However, the mean distance retreated was smaller than that of the northwest glaciers at all time periods. In both the northwest and the southwest, the ranges of individual glacier rates show no clear increase over time, unlike those seen in Figure 4.2.

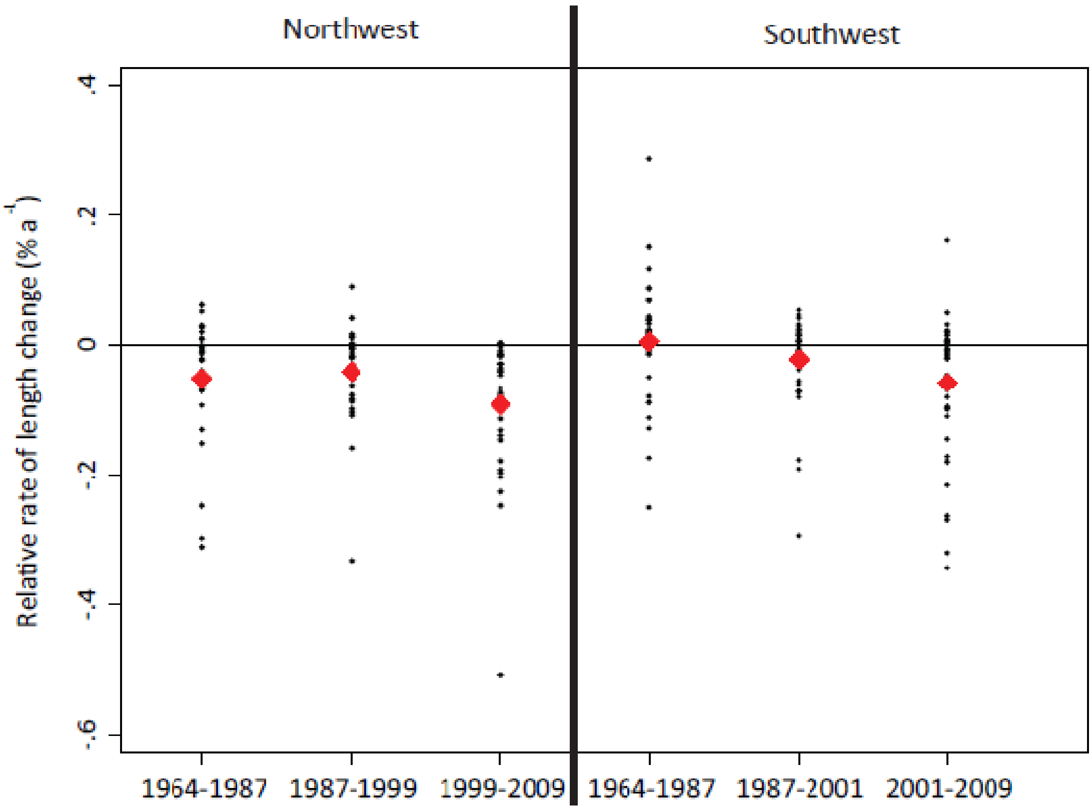


Figure 4.4: Mean and individual annual relative rates of glacier length change calculated for three time steps between 1964 and 2009. The northwest sample size is 33 glaciers, the southwest is 42.

4.2.3 Decadal rate changes from 1943-2009

To investigate variations in glacier length change over shorter time scales, smaller samples of glaciers that were measured in every decade since 1964 are used (Figure 4.5). The dataset is then extended using eight northwest and nine southwest glaciers that were measured prior to 1964 from aerial photographs. Due to the small sample sizes, no definite conclusions can be drawn regarding overall trends, but the results do give an indication of fluctuations in rate that can then be explored further using targeted sampling. In the northwest, the data suggest that the glaciers retreated the shortest distances from 1964-1975, at -0.02% a^{-1}, and underwent greatest retreat the following decade, at -0.13% a^{-1}. However, this rapid mean retreat can be partially explained by the behaviour of Glacier 48 (Farquhar Gletscher), which decreased in length by -0.84 % a^{-1}, 0.5 % faster than any other glacier sampled.

Examination of the absolute retreat data shows that this equates to a reduction in length of -534 m a^{-1}, with other glaciers in this sample retreating by no more than 25 m a^{-1} (Figure 4.6). This sample of glaciers includes main ice sheet outlets 44, 45, 46 and 47, which are located very close to Glacier 48, but underwent very little retreat per year from 1975 to 1987 (for example, see Figure 4.7). As has been previously observed in Section 4.2.1, Glacier 48 also decreased in length rapidly between 1999 and 2009, at an absolute rate of 325 m a^{-1}. Whilst this only equates to a tiny percentage of its overall length, it is a much greater retreat than that observed for any other main ice sheet outlet glacier included in that sample. Excluding Glacier 48 from the calculations for 1975-1987 gives a much slower reduction in length of -0.06% a^{-1}, compared to the previous mean rate of -0.13% a^{-1}. This value is approximately the same as the mean rate of retreat calculated for the period 1953-1964. These results emphasise the point that mean retreat values for small sample sizes are heavily influence by extreme behaviour, so are less reliable indicators than larger sample sizes of the overall glacier behaviour in a region.

In the southwest, Figure 4.5 indicates that a mean advance occurred from 1964-1973, followed by zero change between 1973 and 1987, and switching to overall retreat from 1987-2009. The individual glacier length change data points show that three glaciers underwent particularly rapid advance or retreat from 1964-1973. However, these glaciers have not undergone particularly fast advance or retreat at any other time period. The data for 1953/43-1964 suggest that significant retreat occurred in both the northwest and southwest during these periods, relative to the following decade. This is particularly striking in the southwest region, where the both the mean and maximum distance retreated from 1943-1964 were larger than those of other time period. However, examination of the absolute retreat data does not show this trend to be so extreme. This is because the majority of glaciers included in the 1943/53-1964 samples are relatively small, so a reduction in length of up to 36 m a^{-1} equates to relatively large proportion of their overall length. Without measurements for more glaciers of different sizes, it is impossible to tell whether such extensive relative retreat is representative of the majority of glaciers in this region.

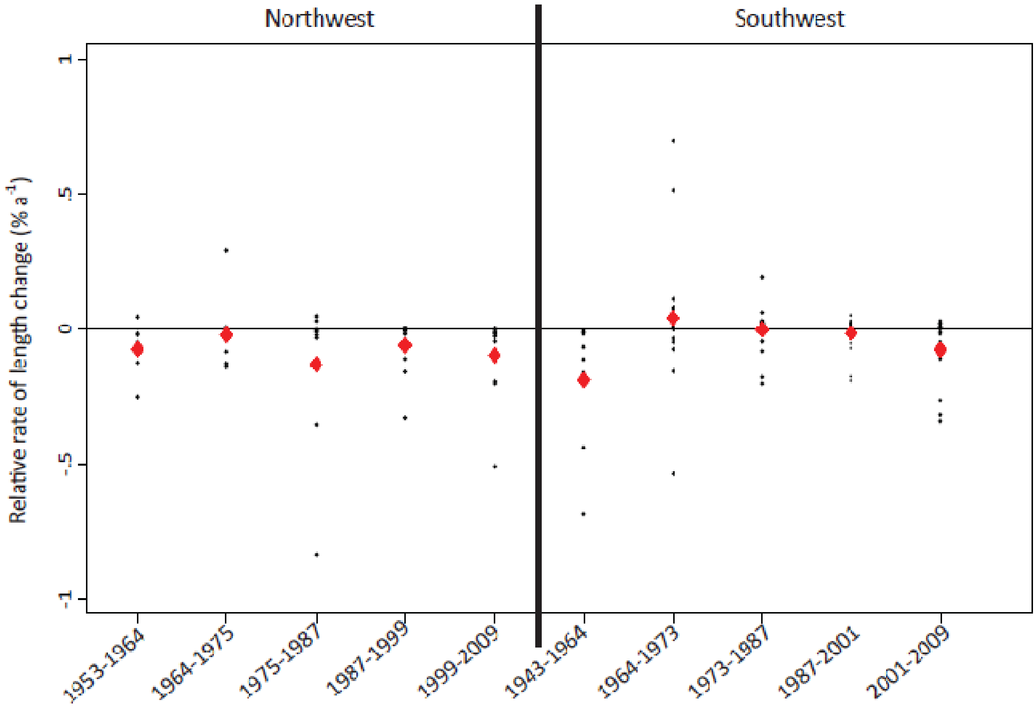


Figure 4.5: Mean and individual rates of annual glacier length change measured at decadal intervals. Figures for 1964-2009 are based on 11 northwest and 18 southwest glaciers, and figures for 1943/53-1964 on 8 northwest and 9 southwest glaciers.

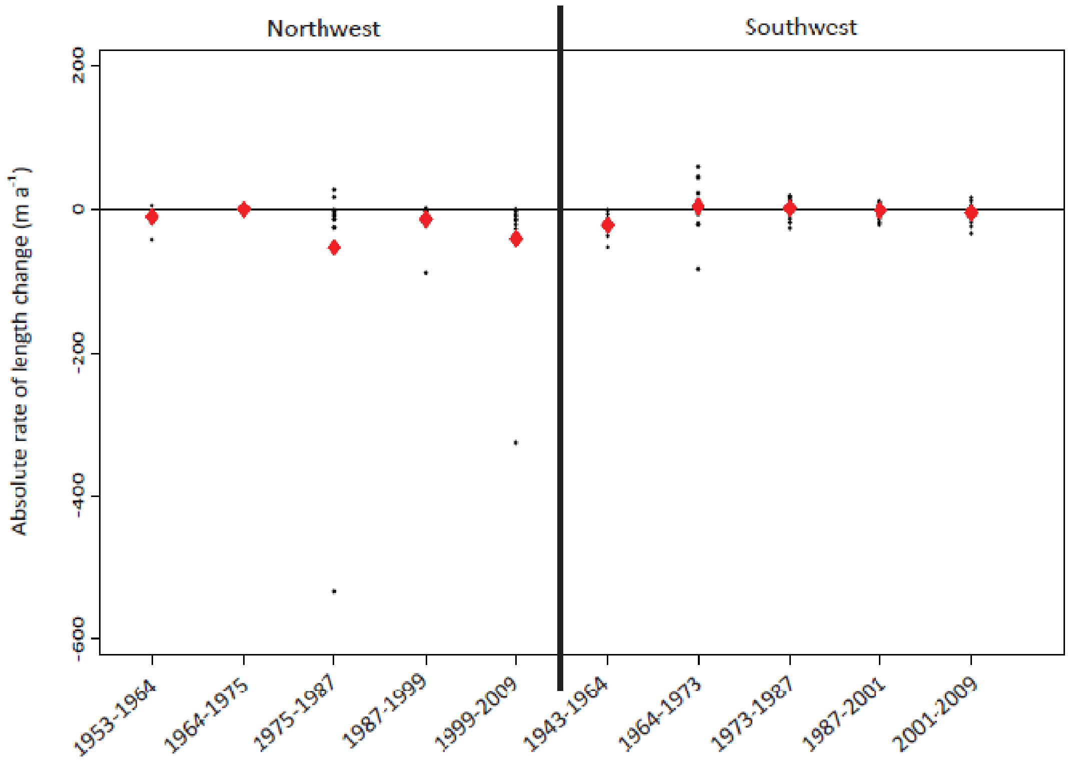


Figure 4.6: Mean and individual rates of absolute glacier length change measured at decadal intervals, using the same glacier samples as shown in Figure 4.5.

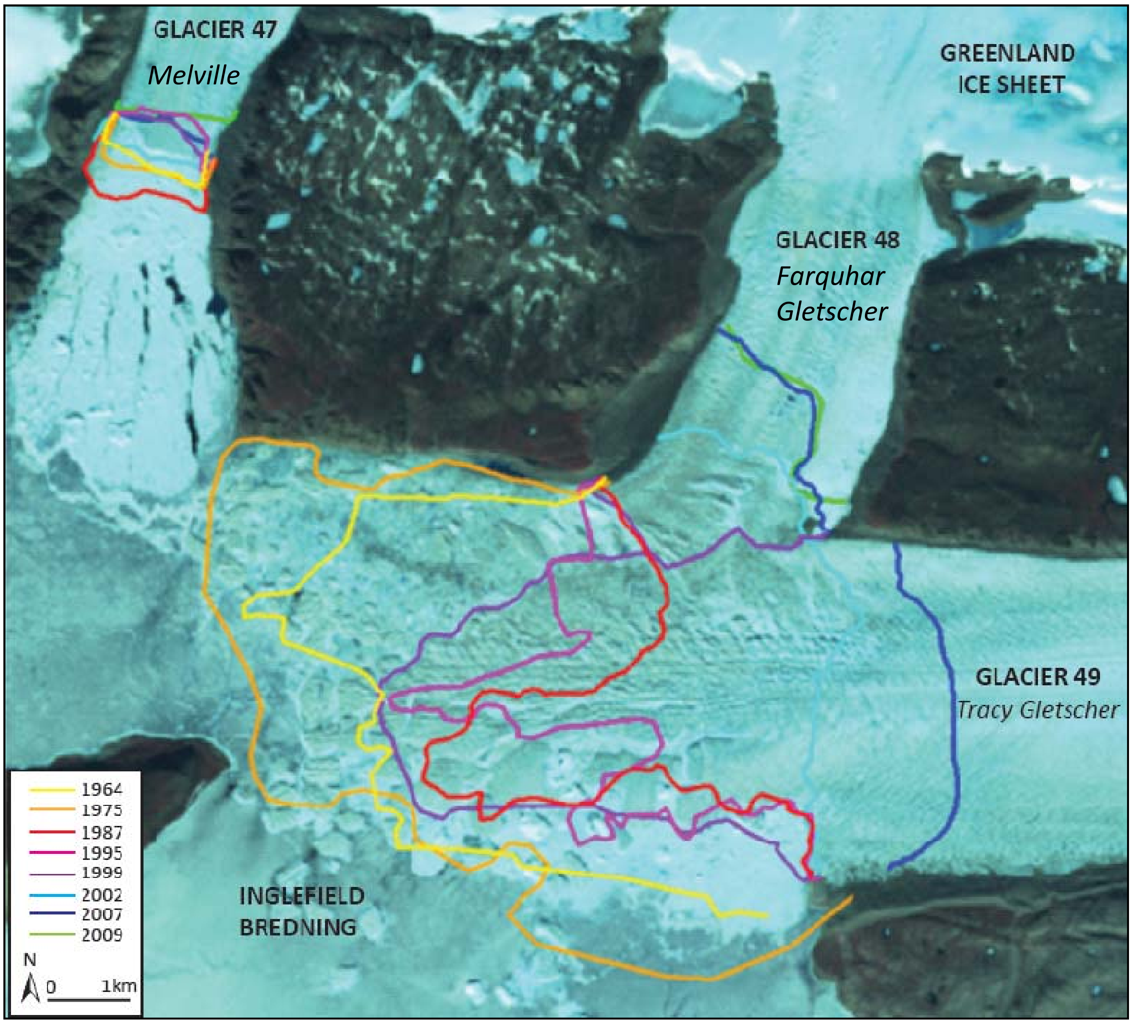


Figure 4.7: Terminus positions of Glaciers 47, 48 and 49 mapped between 1964 and 2009. Background image is the 1999 Landsat TM base image, displayed using bands 4,3,2 (R,G,B).

4.2.4 Detailed rate changes for selected periods: 1964-2001

Data are available at more time steps for the periods from 1987-1999/2001 in the northwest and southwest, so they are analysed in more detail here (Figure 4.8). Prior calculations of glacier length change in the northwest suggested that a mean retreat of between -0.04 and -0.06% a^{-1} had occurred. This was relatively small compared data for other time periods (see Figures 4.4 and 4.5). The larger dataset examined here indicates an even slower overall retreat rate of just -0.01% a^{-1} between 1987 and 1999. Breaking this time period down into two steps reveals that in the northwest, no change in mean glacier length occurred between 1987 and 1992, followed by only slow mean retreat of -0.02% a^{-1} from 1995-1999.

In the southwest, previous estimates of glacier length change indicated that slow retreat of ~0.02% a^{-1} had occurred between 1987 and 2001, whereas the sample of glaciers examined here underwent a slighter faster mean retreat of -0.03 % a^{-1} (Figure 4.8). Breaking this time period down into two steps, however, suggests that no change in mean glacier length occurred from 1987-1992, but that this was followed by rapid mean retreat 1992-2001

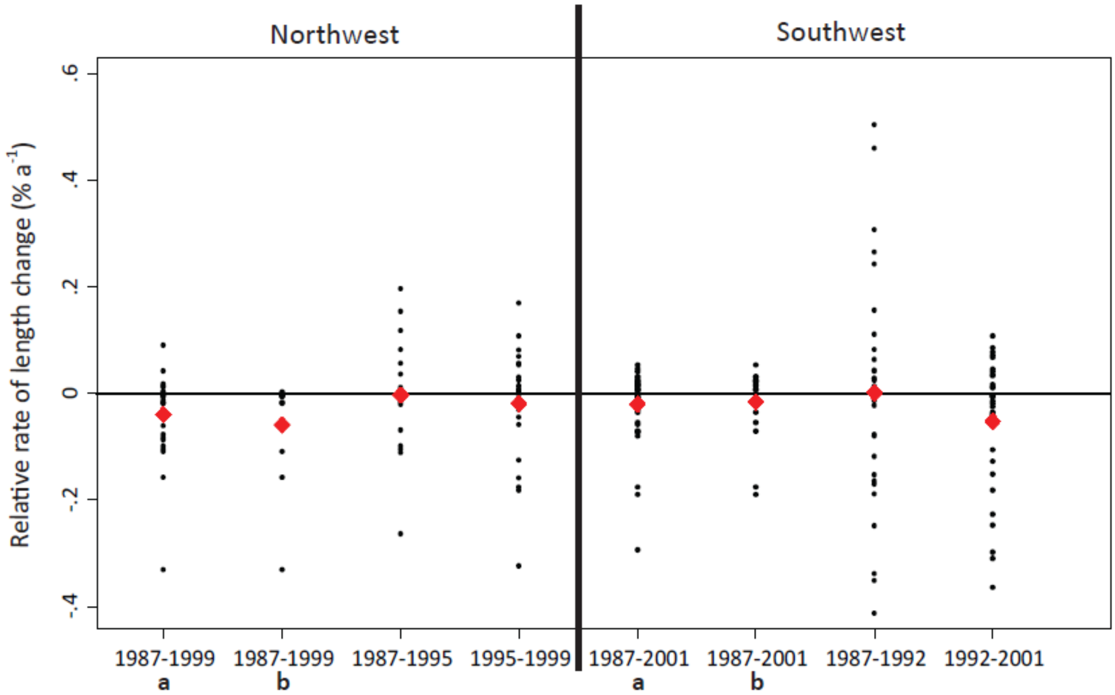


Figure 4.8: Mean and individual rates of relative glacier length change between 1987 and 1999/2001. Values 'a' are the decadal data shown in Figure 4.5, derived from 11 northwest and 18 southwest glaciers; values 'b' are the data shown in Figure 4.4, derived from 33 northwest and 42 southwest glaciers. The remaining data are calculated from samples of 25 northwest and 33 southwest glaciers.

4.2.5 Detailed rate changes for selected periods: 1999-2009

Previous studies have suggested that glaciers in Greenland have undergone accelerated retreat during the past decade (e.g. Joughin *et al.*, 2004; Howat *et al*., 2008; Box, 2009; see Chapter 2, Section 2.3.3). The results presented in Sections 4.2.1 to 4.2.3 suggest that relatively rapid retreat may have occurred in both the northwest and southwest study areas between 1999/2001 and 2009. To examine this trend more closely, samples of glaciers that were measured at several time steps during the past decade are used (Figure 4.9). These consist of 62 glaciers measured at 4 time steps in the northwest, and 35 glaciers measured at three time steps in the southwest. The data suggest that the mean distance retreated per year in the northwest remained stable from 1999 to 2002, but decreased during 2007-2009, whilst the range of individual glacier length changes increased significantly. Examination of the individual data points reveals that two glaciers advanced and retreated much greater distances per year from 2007-2009 than the other sixty glaciers. These were icefield outlet glacier 84 (advanced) and icefield margin number OI011. Icefield margin OI011 was also one of the two glaciers that underwent the most retreat from 1999-2002 and 2002-2007.

Unsurprisingly, examination of absolute retreat data gives a different picture (Figure 4.10), with main ice sheet outlet Glacier 48 (Farquhar) retreating the greatest distance during all three time periods. However, the distance it retreated per year did decrease significantly, from -621 m a^{-1} during 1999-2002 to -131 m a^{-1} during 2007-2009. Neighbouring Glacier 50 (Heilprin Gletchser) also retreated large distances from 1999-2002 and 2002-2007, of -381 m a^{-1} and -174 m a^{-1} respectively. Nearby, the main ice sheet Glacier 47 (Melville Gletscher) displayed very different behaviour, because it advanced by 189 m a^{-1} during 1999-2002 and then retreated by -119 m a^{-1} during 2002-2007. This equates to relative rates of +0.33 % a^{-1} and -0.21 % a^{-1}, respectively.

The southwest shows no signs of any significant changes in mean distance retreated between 2001 and 2009, and the mean distance retreated is smaller than that of the northwest glaciers. This observation is supported by Figures 4.2, 4.4 and 4.5. However, the absolute data indicate that the mean distance retreated per year increased from 2007-2009, but because this increase mainly applied to the larger glaciers this does not equate to a significantly faster mean retreat as a proportion of overall length. We cannot be certain that the trends observed for 2007-2009 in the northwest and southwest are an accurate representation of actual changes, because the measurement errors are very high over such a short time period (±0.05% a^{-1} or ±24.3 m a^{-1}; see Chapter 3, Section 3.6.3). These outweigh the observed mean rate changes.

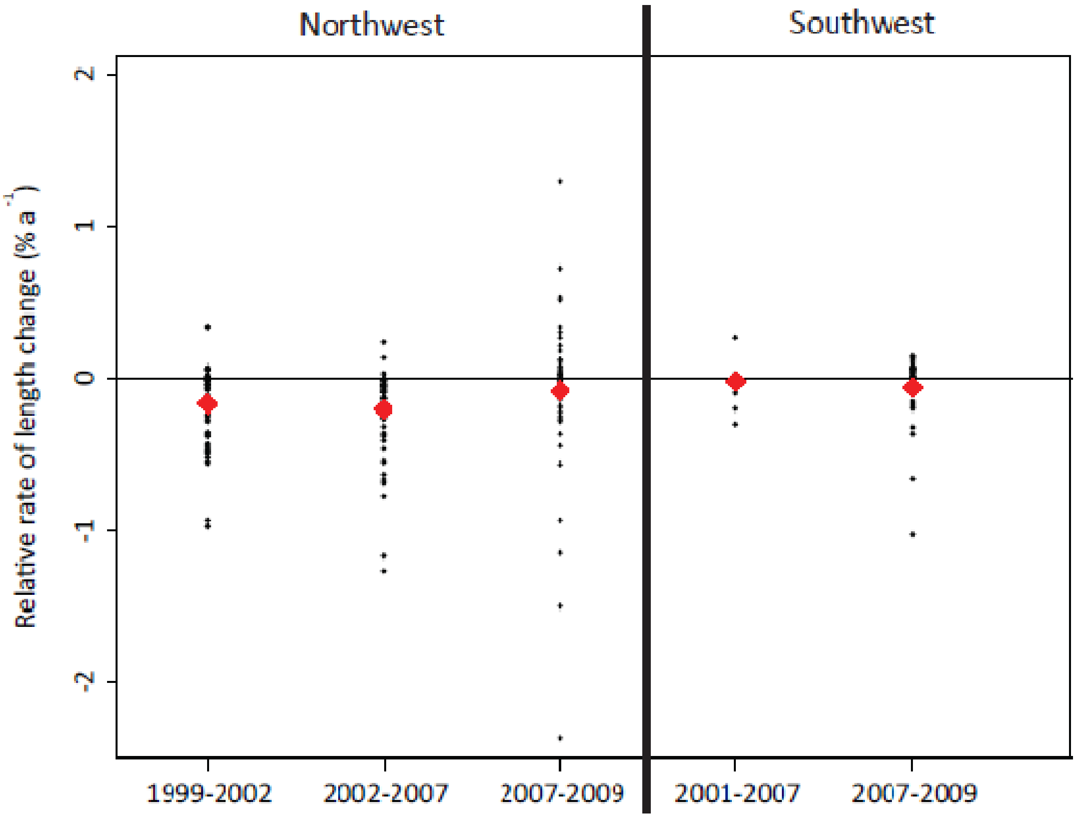


Figure 4.9: Mean and individual rates of relative glacier length change over the past decade. Figures based on 62 glaciers in the northwest, and 35 glaciers in the southwest.

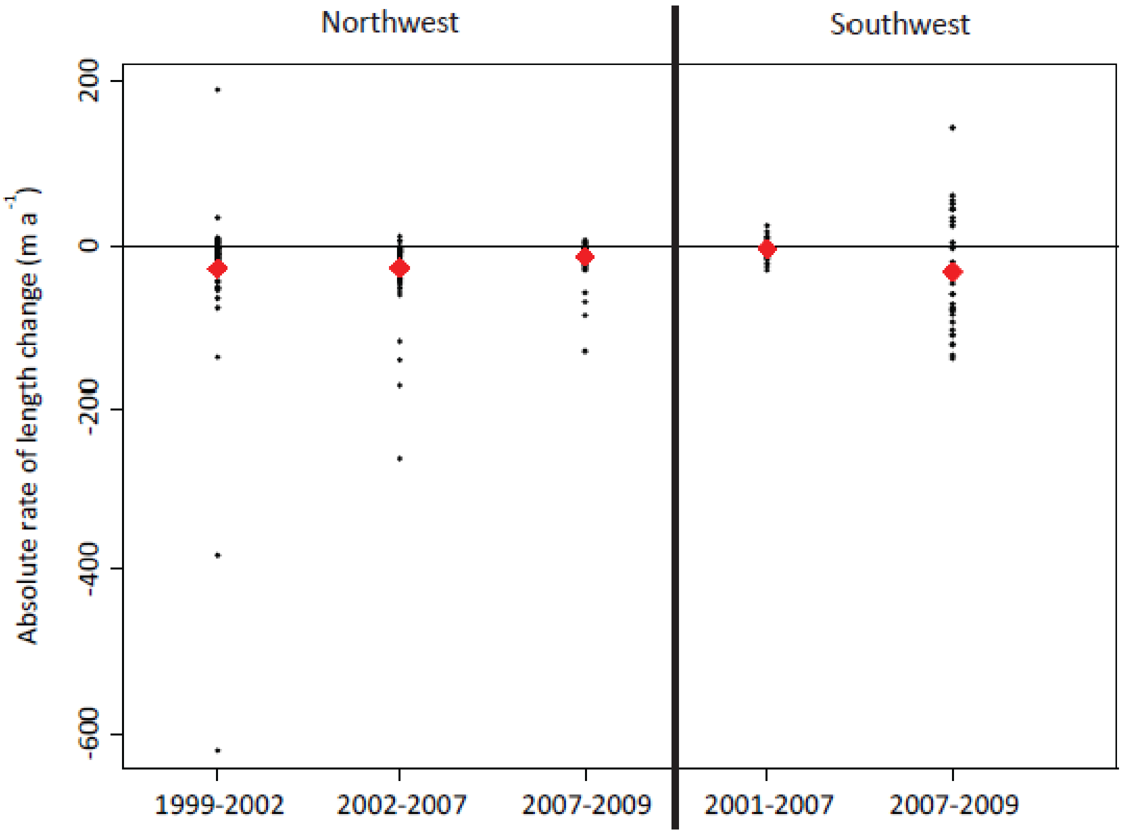


Figure 4.10: Mean and individual rates of absolute glacier length change over the past decade, based on the same glacier samples as shown in Figure 4.9.

4.2.6 Surge-type glaciers

Two possible surge-type glaciers were identified in the northwest study area (Chapter 3; Section 3.5.4). Glacier 59 (Harald Moltke Brae) is a large tidewater ice sheet outlet glacier located in the southeast corner of the study area, which has been observed to surge in the past (Mock, 1966). In this study, it was mapped at seven time steps between 1953 and 2009, and observed to have retreated by 5.6% (4.8 km) overall during this time period (Figures 4.11 and 4.12). This retreat did not occur at a steady rate, however, as the glacier retreated from 1953-1964, then readvanced back to its 1953 position by 1972, before retreating between 1972 and 2009.

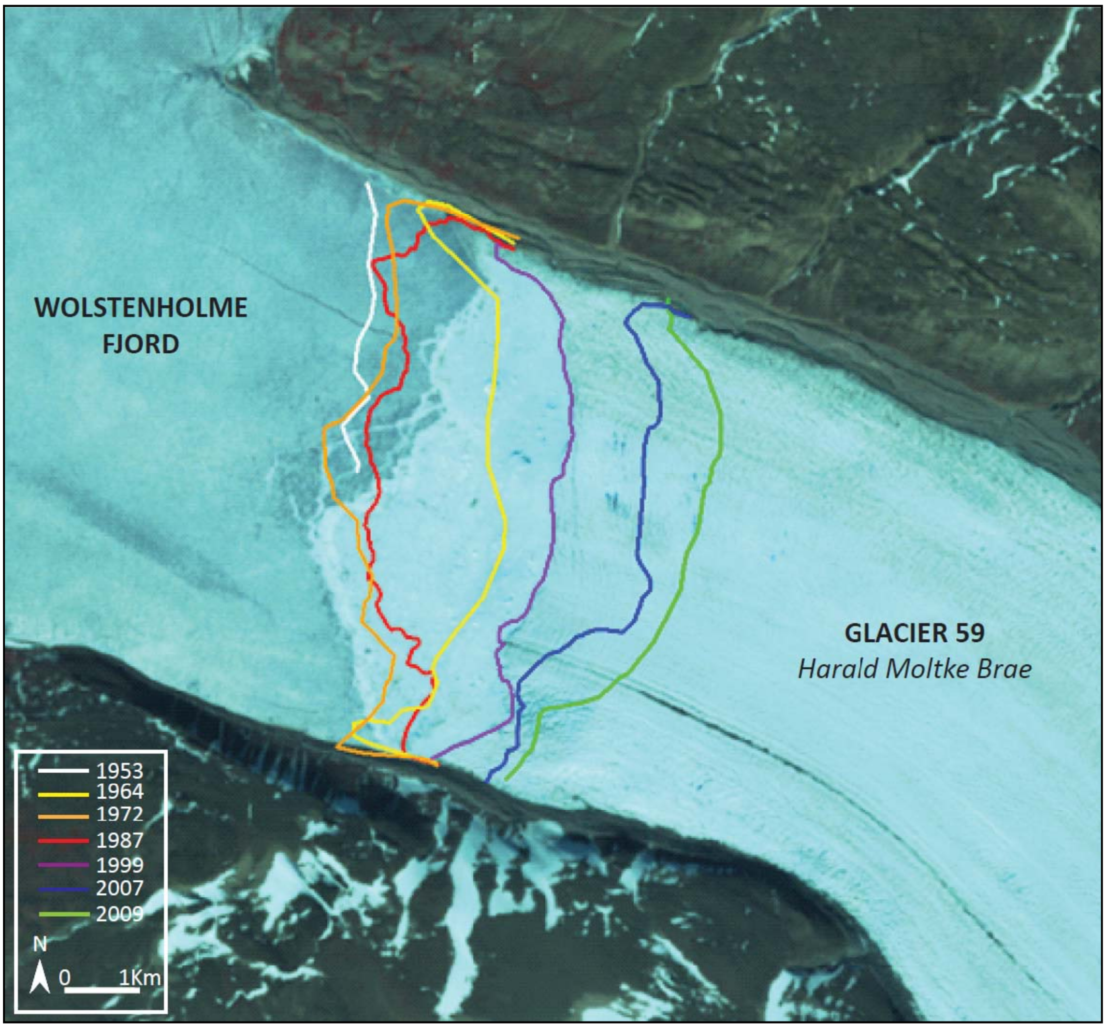


Figure 4.11: Terminus position of Glacier 59 (Harald Moltke Brae) mapped at seven time steps between 1953 and 2009.

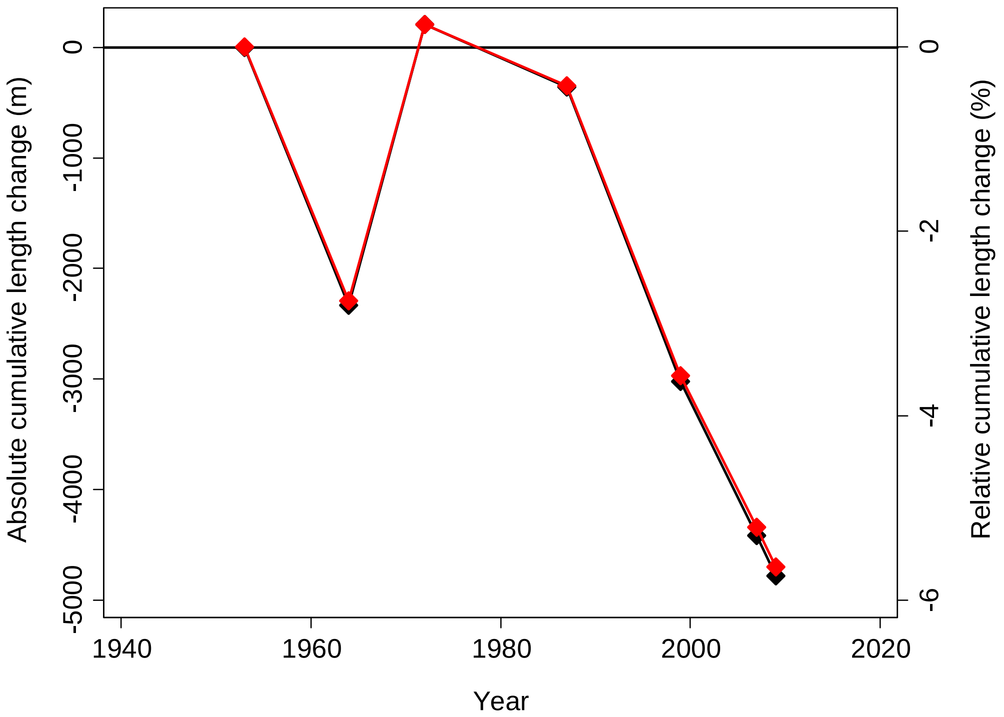


Figure 4.12: Absolute (black) and relative (red) cumulative length change for Glacier 59 (Harald Molte Brae) during the second half of the 20th century, relative to its first measured position in 1953.

The second glacier identified as possible surge-type is Glacier 75 (Berlingske Brae), an ice cap outlet glacier draining the west side of the North Ice Cap. This glacier was mapped at six time steps between 1953 and 2009, and the results revealed that it had advanced overall during that time period, by 8.2% (3.1 km) (Figures 4.13 and 4.14). This advance was particularly rapid from 1964-1987. No other non-surge type glacier has undergone such a rapid and prolonged advance in either the northwest or southwest study areas.

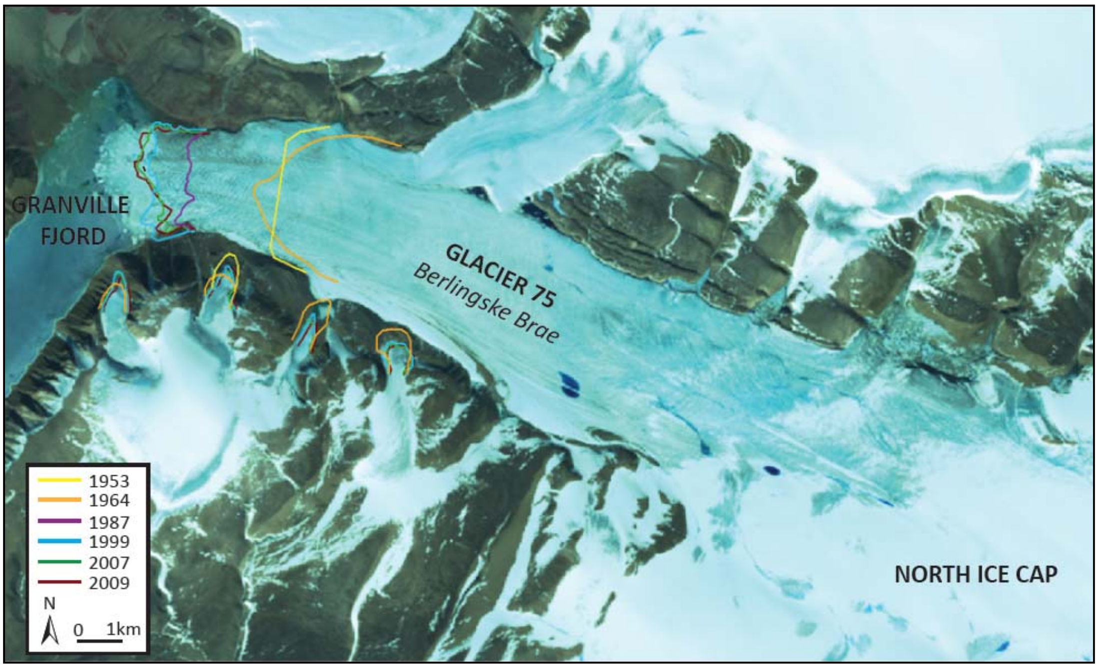


Figure 4.15: Terminus position of Glacier 75 (Berlingske Brae) mapped at six time steps between 1953 and 2009.

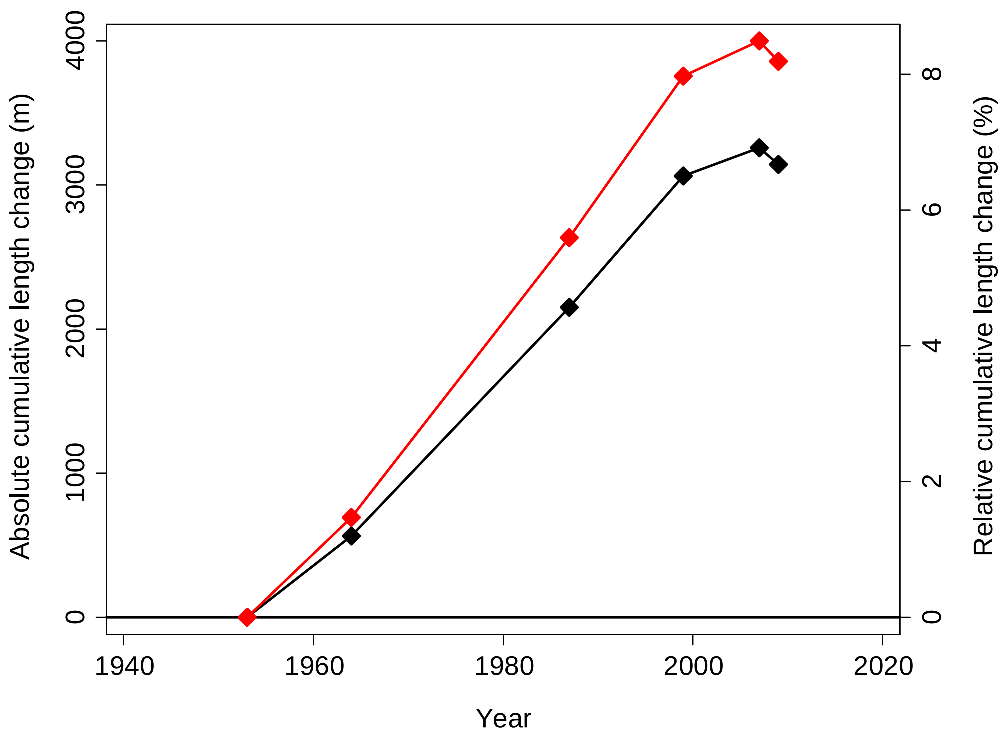


Figure 4.16: Absolute (black) and relative (red) cumulative length change for Glacier 75 (Berlingske Brae) during the second half of the 20th century, relative to its first measured position in 1953.

4.2.7 Summary

To summarise the data presented in Section 4.2, graphs showing the cumulative absolute and relative length changes of glaciers measured at four time steps in the northwest and southwest are shown in Figure 4.15. Based on these graphs and those presented in the preceding sections it can be seen that glaciers in the northwest had a mean total retreat of ~650 metres, or 2.8% between 1964 and 2009, and that mean rate of retreat increased over time. In the southwest, glaciers had a mean total retreat of ~100 metres, or 0.6%, and distance retreated from 2001-2009 was no further than that from the LIA-1964.

Cumulative length change data for glaciers measured at every decade is shown in Figure 4.16. From this graph and those presented in Section 4.2.3 it would appear that glaciers have retreated by ~1250 metres, or 8%, between 1964 and 2009. This is further than is indicated by the data in Figure 4.15 and is probably an overestimate that has been skewed by the particularly extensive retreat of Glacier 48 (Tracy Gletscher). Glacier retreat in the northwest appears to have fluctuated between fast and slow rates every decade. The cumulative data for the southwest (Figure 4.16) give a total mean retreat of approximately 50 metres, or 1%, which is more similar to the result shown in Figure 4.15. The decadal rate data suggest that the glaciers retreated large distances from 1943-1964, then advanced from 1964-1973. Since 1987 they have retreated slowly. In conclusion, these data indicate that glaciers in the northwest have retreated further than those in the southwest at almost all time periods since the Little Ice Age.

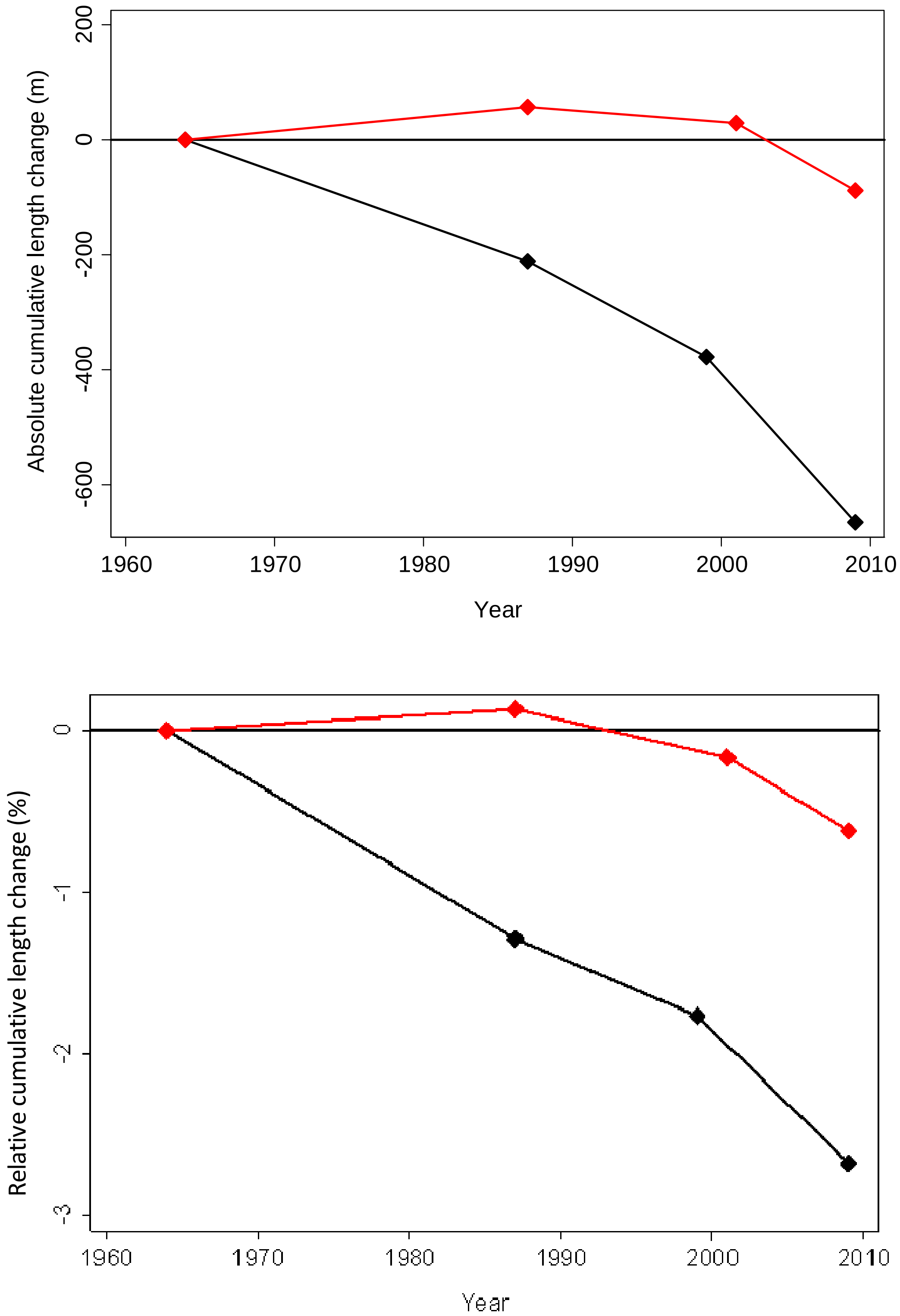


Figure 4.15: Mean absolute and relative cumulative length change of glaciers in the northwest (black) and southwest (red) that were mapped at four time steps between 1964 and 2009. See Section 4.2.2 for more details on these glaciers.

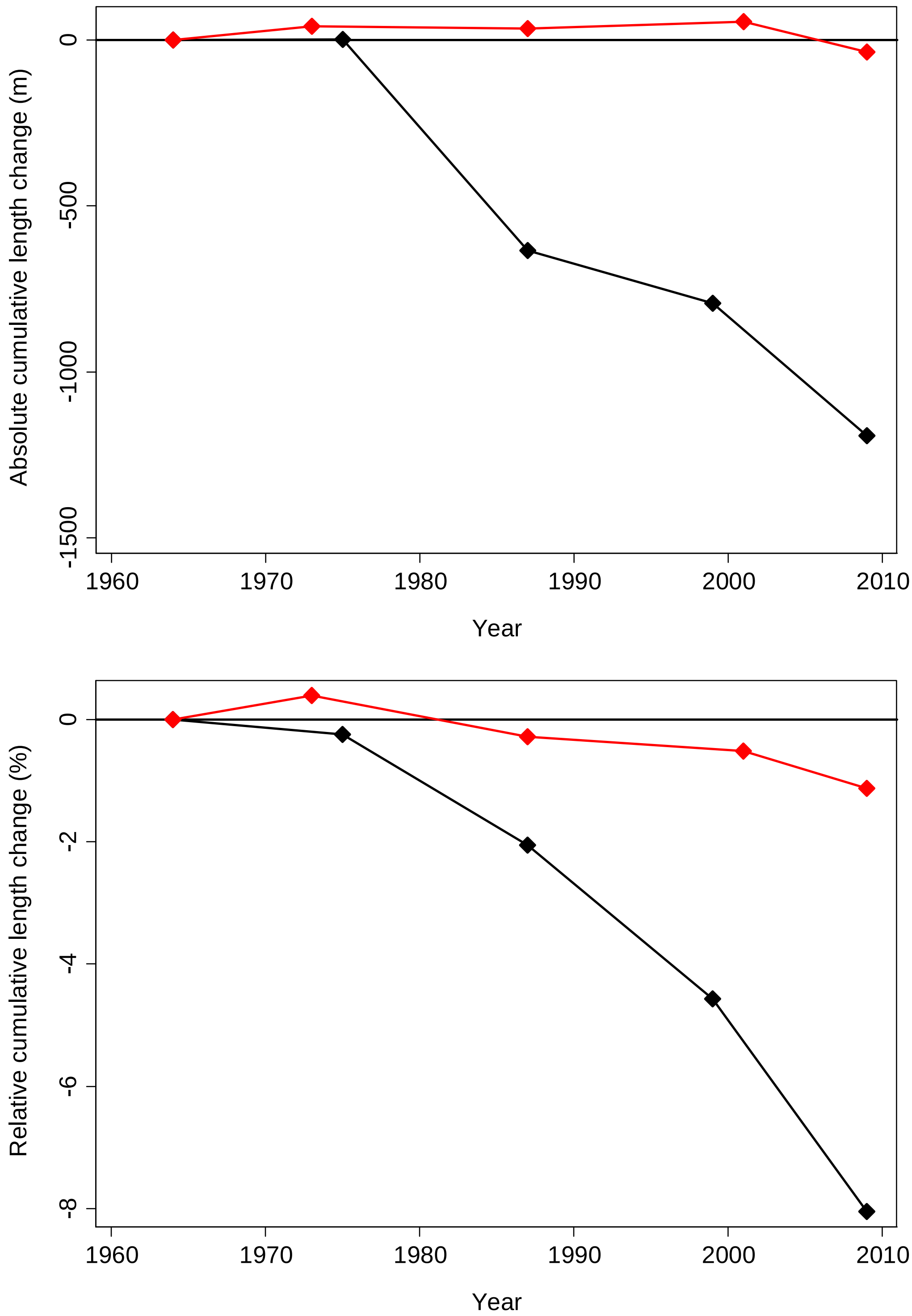


Figure 4.16: Mean absolute and relative cumulative length change of glaciers in the northwest (black) and southwest (red) that were mapped at decadal intervals between 1964 and 2009. See Section 4.2.3 for more details on these glaciers.

Chapter 5

Results II: Drivers and controls of glacier fluctuations

5.1 Introduction

It is generally accepted that variations in local climate, (most notably air temperature and precipitation), are the main drivers of glacier length and mass balance changes (e.g. Oerlemans, 2005; IPCC, 2007; WGMS, 2008a). Previous work in Greenland suggests that the response of different glacier classes to climate changes varies, with the smaller independent ice cap and mountain glaciers responding earlier than the larger ice sheet outlet glaciers (Gordon, 1981; Weidick *et al.* 1992, Yde and Knudsen, 2007). Research also indicates that the timing and magnitude of glacier length changes in response to climate is partly controlled by glacier terminus environment (Weidick, 1959; Warren, 1991; Warren and Glasser, 1992). In addition, glacier characteristics such as slope, aspect, area, length and terminus elevation have been shown to have some impact on the magnitude of length change in Greenland and worldwide (Oerlemans, 2005; DeBeer and Sharp, 2007; Yde and Knudsen, 2007; Citterio *et al.*, 2009). The aim of this chapter is to investigate whether these factors may have influenced glacier length changes in northwest and southwest Greenland. The links between the regional glacier fluctuations presented in Chapter 4 and local air temperature and precipitation data are first explored in Section 5.2. Detailed analysis of length changes for glaciers in different classes and terminus environments is then undertaken in Sections 5.3 and 5.4, respectively. Finally, possible relationships between length changes and aspect, area, length, slope and minimum elevation of glaciers are examined briefly in Section 5.4. A summary of the key findings of this chapter is presented in Section 5.5.

5.2 Glacier length change and climate

For the present study, air temperature and precipitation data from eight meteorological stations in the northwest and southwest study areas are used to reconstruct local climate trends (Figure 5.1 and Table 5.1). These records date back to 1950 in the northwest and 1880 in the southwest, and were obtained from the Danish Meteorological Society (DMI; www.dmi.dk) and the Goddard Institute for Space Studies (GISS; http://data.giss.nasa.gov). Data collected prior to 1957 should be treated with caution as it often contains errors arising from site relocation, changes in instruments and changes in measurement techniques and frequency. Such errors are less of a problem after the methods for collecting meteorological data were standardised in 1957 (Box, 2002). Sea surface temperatures may also play a significant role in triggering tidewater glacier retreat through terminus melting (Rignot *et al.,* 2001), but there is a lack of detailed, accurate, long-term ocean temperature data for Greenland, so only air temperatures and precipitation were considered in this study.

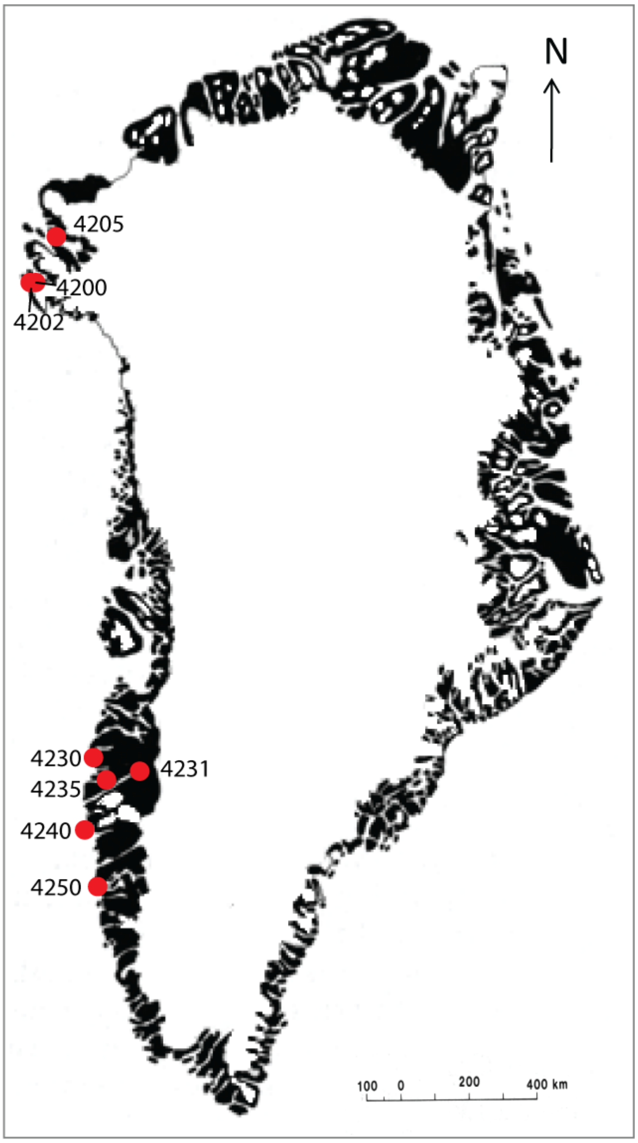


Figure 5.1: Map of Greenland showing location of meteorological stations used in this study. See Table 5.1 for details.

Station	Start date	Stop date	Latitude	Longitude	Elevation (m a.s.l.)
4200 Dundas	01/01/1961	31/08/1983	76 34	68 48	21
4202 Thule b	01/01/1974	27/11/2006	76 32	68 45	77
4205 Thule a	02/01/1964	30/06/1980	77 29	69 12	14
4230 Sisimuit	01/01/1961	22/06/2001	66 55	53 43	10
4231 Kangerlussuaq	01/05/1973 01/01/1990	31/12/1989 -	67 00	50 48	50
4235 DYE 1	13/03/1974	18/09/1989	66 38	52 52	1439
4240 Maniitsoq	01/01/1961	30/01/1987	65 24	52 52	25

Table 5.1: Details of the meteorological stations used in this study.

5.2.1 Air temperature trends

Air temperature data from two meteorological stations in the northwest, and two in the southwest, are shown in Figure 5.2. Overall, temperatures in the southwest are higher than those in northwest, by between 4 and 10°C. Whilst the temperatures recorded at the two northwest stations (Dundas and Thule) are very similar, those measured at Kangerlussuaq in the southwest are lower than those of Nuuk. This is not unexpected, as Nuuk is a coastal station whereas Kangerlussuaq is located inland, where temperatures tend to be lower as a result of the closer proximity to the ice sheet (Weidick, 1995). An 5-year moving average has been applied to each of the temperature records, and some broad trends can be identified.

In the southwest, air temperatures at Nuuk appear to have increased steadily between 1880 and 1930, then remained relatively high between 1930 and 1965. After 1965, temperatures decreased, although with large short-term fluctuations. This was followed by a sharp increase in temperatures between 1993 and 2004, with a possible slight decrease from 2004-2009. Current temperatures are similar to the mean, but lower than the maximum, of those recorded during the 1930s. Data from Kangerlussuaq meteorological station are only available for the twenty year period between 1950 and 1970, so long-term trends cannot be assessed. It is difficult to tell if the data match the trends observed at Nuuk during this time period, but it appears that large short-term fluctuations occurred. In the northwest, air temperatures at both Dundas and Thule remained fairly stable between 1950 and 1980, before decreasing overall between 1980 and 2000, then increasing to their highest recorded level between 2000 and 2009. It would also appear that shifts in air temperature trends in the northwest broadly match those observed in the southwest, with no obvious lag time.

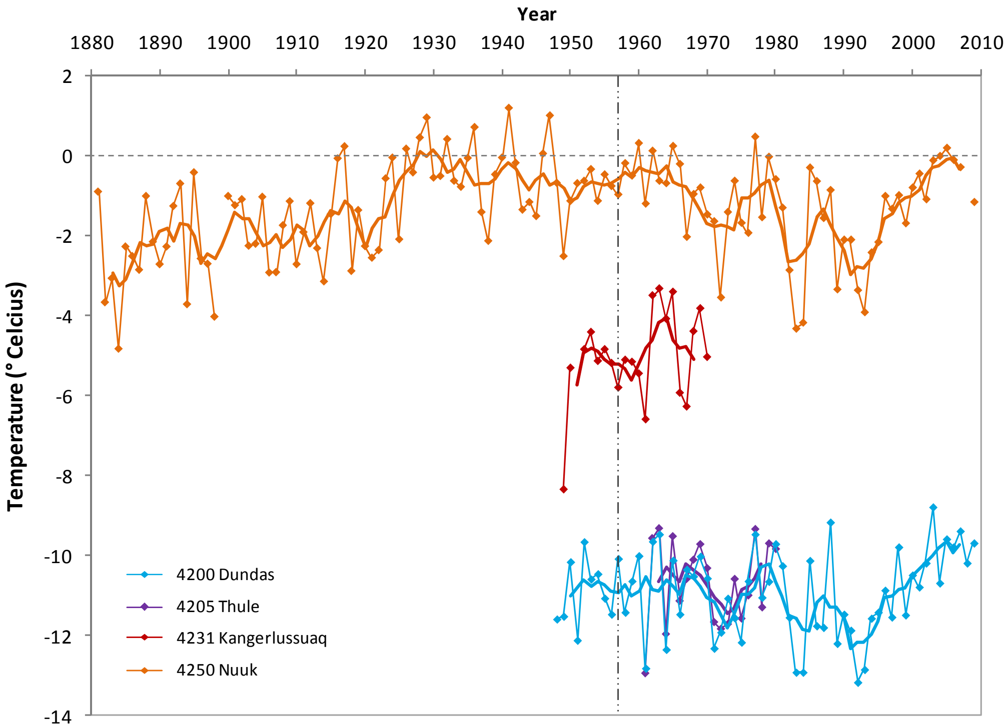


Figure 5.2: Air temperature data from four stations in southwest Greenland (4250 and 4231) and northwest Greenland (4205 and 4200). Note that there may have been a break in measurements at Nuuk, so data prior to 1957 may not be homogenous. Data for Nuuk, Kangerlussuaq and Dundas downloaded from the Goddard Institute of Space Studies (http://data.giss.nasa.gov). Data for Thule downloaded from the Danish Meteorological Institute (DMI; www.dmi.dk). The solid coloured lines are the 5-year moving averages.

5.2.2 Precipitation trends

Precipitation data from three northwest and 5 southwest meteorological stations are presented in Figure 5.3, with 5-year moving averages. In general, mean annual precipitation is highest in the southwest study area, although there are significant variations between stations. The inland meteorological stations (DYE 1 and Kangerlussuaq) have recorded much lower levels of precipitation than the coastal stations, equivalent to that measured in the northwest. General trends are very hard to identify from this data; mean annual precipitation at Nuuk appears to have increased sharply after 1953, but it is possible that this is simply due to changes to the data collection method (as discussed above). A further overall increase in precipitation at Nuuk appears to have occurred after 1990. The records from other southwest stations are very varied and are too short to allow the long-term trends to be assessed. In the northwest, the records suggest that levels of precipitation are similar at all three meteorological stations. Because measurements are only available for short time periods it is hard to assess long-term trends, but there may have been a slight increase in mean annual precipitation between 1960 and 2010.

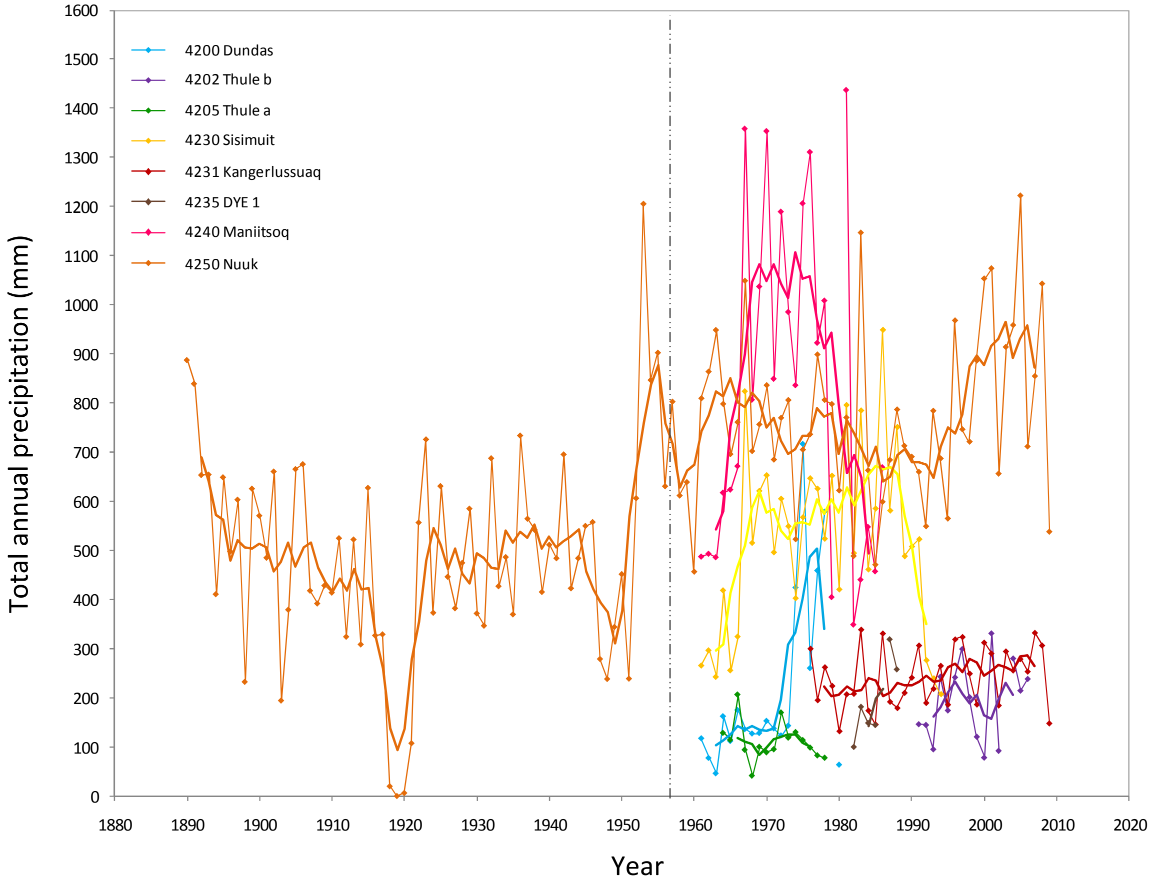


Figure 5.3: Total annual precipitation data from eight stations in southwest Greenland (4230- 4250) and northwest Greenland (4200-4205). Data collection was standardised in 1957 (black dotted line); measurements made before this period may not be as reliable. The solid coloured lines are the 5-year moving averages. Data are from Carstensen and Jorgensen (2010).

5.2.3 Comparing air temperature data to glacier fluctuations

Comparing glacier fluctuations to the air temperature and precipitation data is very difficult, partly because of possible errors in the climate data, and partly because glacier measurements have only been made at a maximum of 11 time steps. The air temperature data are compared to mean rate of glacier length change measured at four time steps between 1964 and 2009 in Figure 5.4, based on samples of 33 northwest and 42 southwest glaciers. If glacier behaviour and air temperature are correlated, we would expect to see more rapid glacier retreat following periods of high temperatures (Oerlemans, 2005). However, in the southwest the glaciers advanced overall between 1964 and 1987, following a period of prolonged high temperatures between 1920 and 1965. Glaciers then retreated overall between 1987 and 2001 whilst air temperatures declined. These results could be due to a lag between climate changes and glacier terminus response, but this theory is not supported by the recent rapid rate of glacier retreat (from 2001-2009), which correlates very closely to the significant rise in air temperatures since the 1990s. Glacier behaviour appears to more closely match temperature trends in the northwest, as a decrease in air temperature between 1980 and 2000 is matched by a slower rate of glacier retreat, whilst the increase in temperatures from 1990 to 2009 correlates to an increase in distances retreated.

The air temperature data are compared to a smaller sample of 11 northwest and 18 southwest glaciers that were measured at decadal intervals in Figure 5.5. In this figure temperature and mean rate of length changes appear more closely correlated in the southwest. Southwest glaciers retreated large distances between 1943 and 1964 during the period of high temperatures from 1920-1965, and the subsequent advance and slow retreat between 1964 and 2001 may be due to the steady decline in temperature during this period. As in the previous figure, glaciers retreated greater distances from 2001-2009 as temperatures increased. There is no obvious correlation between mean decadal rate of retreat and air temperature in the northwest.

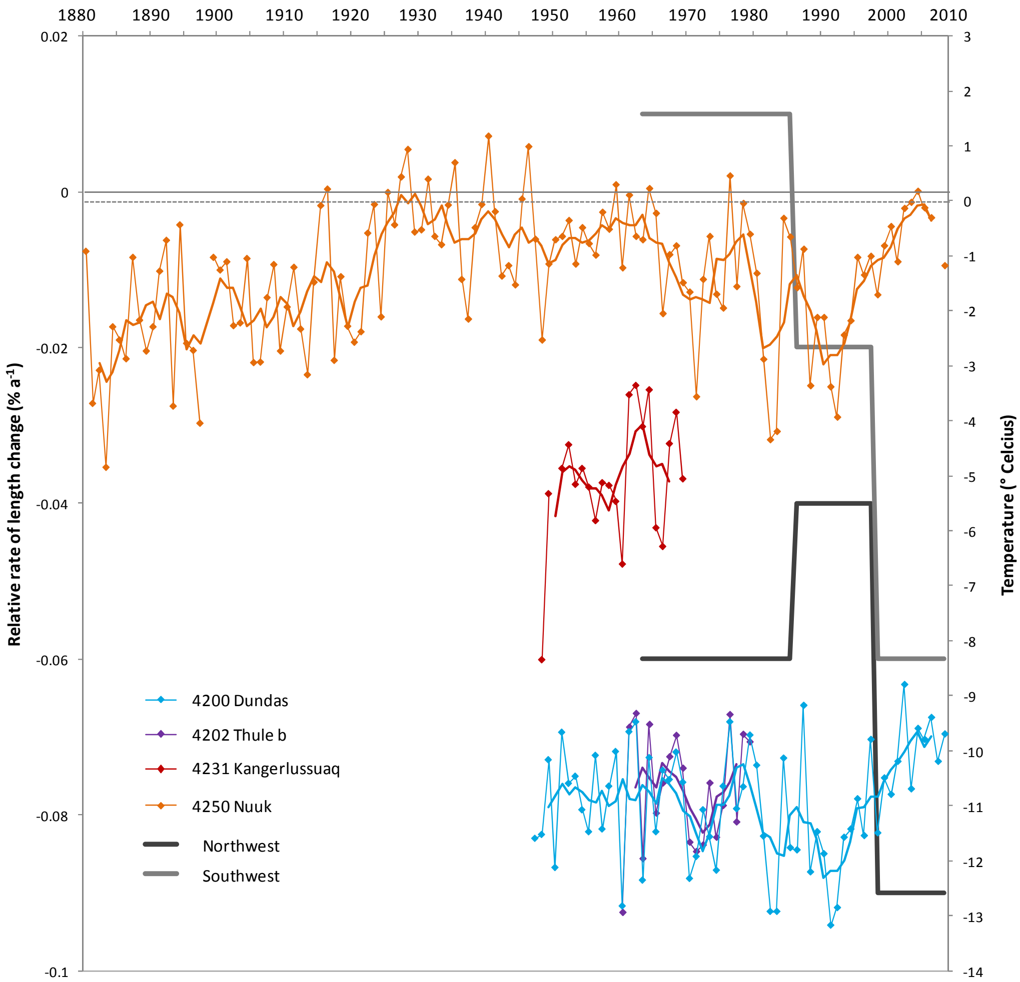


Figure 5.4: Graph showing mean relative rate of glacier length change measured at 4 time steps between 1964 and 2009 (grey lines), and air temperature data (coloured lines), during the twentieth century. Glacier data are based on samples of 33 northwest and 42 southwest glaciers. The grey horizontal solid and dashed lines mark 0% and 0°C, respectively. The solid coloured lines are the 5-year moving averages.

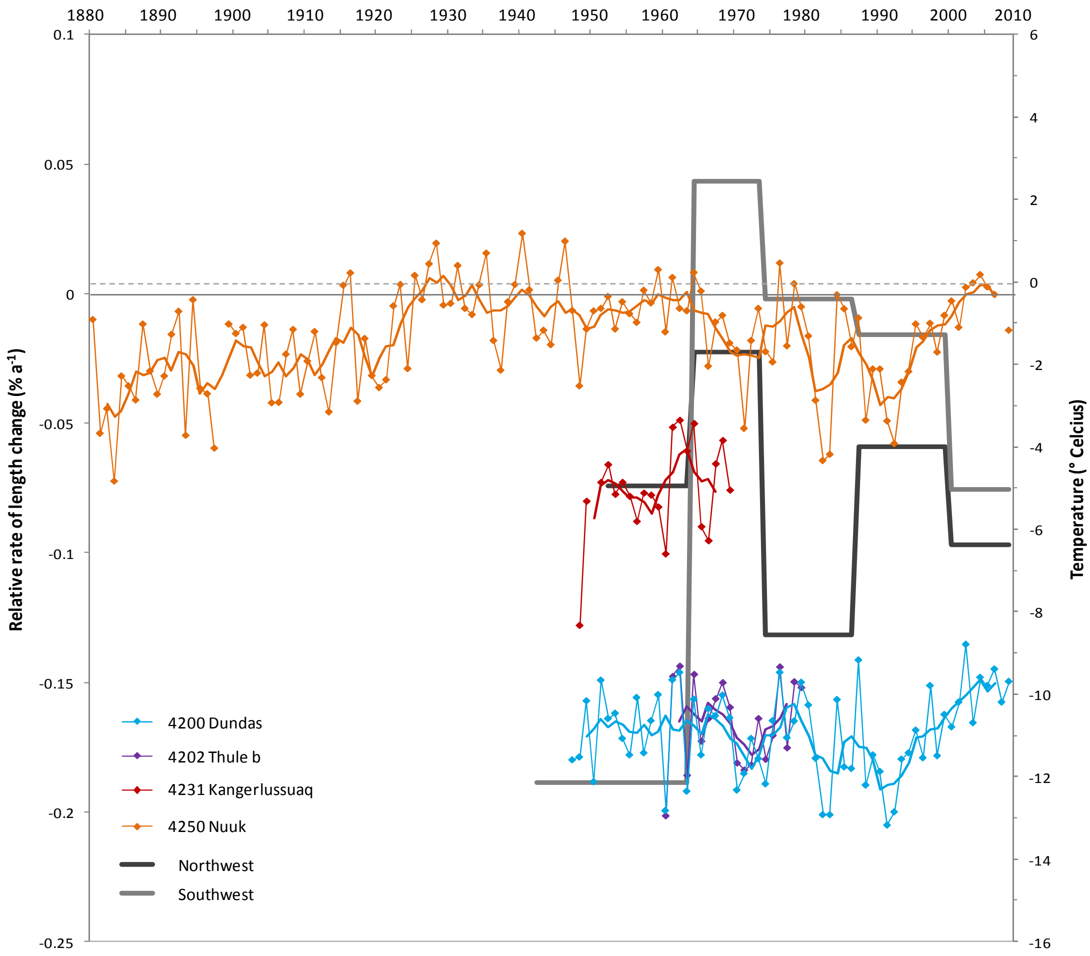


Figure 5.5: Graph showing mean decadal relative rate of glacier length change (grey lines) and air temperature data (coloured lines) during the twentieth century. Glacier data for 1943/53-1964 are based on samples of 8 northwest and 9 southwest glaciers. Data for 1964-2009 are based on 11 northwest and 18 southwest glaciers. The grey horizontal solid and dashed lines mark 0% and 0°C, respectively. The solid coloured lines are the 5-year moving averages.

5.2.4 Comparing precipitation data to glacier fluctuations

Precipitation data from selected meteorological stations are compared to rates of glacier length change measured at four time steps between 1964 and 2009 in Figure 5.6. Davies and Krinsley (1962) have previously observed that a decrease in precipitation was correlated with faster glacier retreat in the northwest, whilst increased precipitation resulted in slower retreat or advance. It is impossible to determine whether glacier fluctuations in the northwest study area are correlated to precipitation based on Figure 5.6, due to the lack of long-term meteorological data. In the southwest, the data indicate that the larger distances retreated from 2001-2009 coincided with the significant increase in precipitation after 1990, which is unexpected. Precipitation data are also compared to decadal glacier fluctuations in Figure 5.7. The switch from significant retreat between 1943 and 1964 to advance from 1964-1973 in the southwest could be due to apparent sharp increase in precipitation after 1950, although it is not certain that it is not due to measurement error.

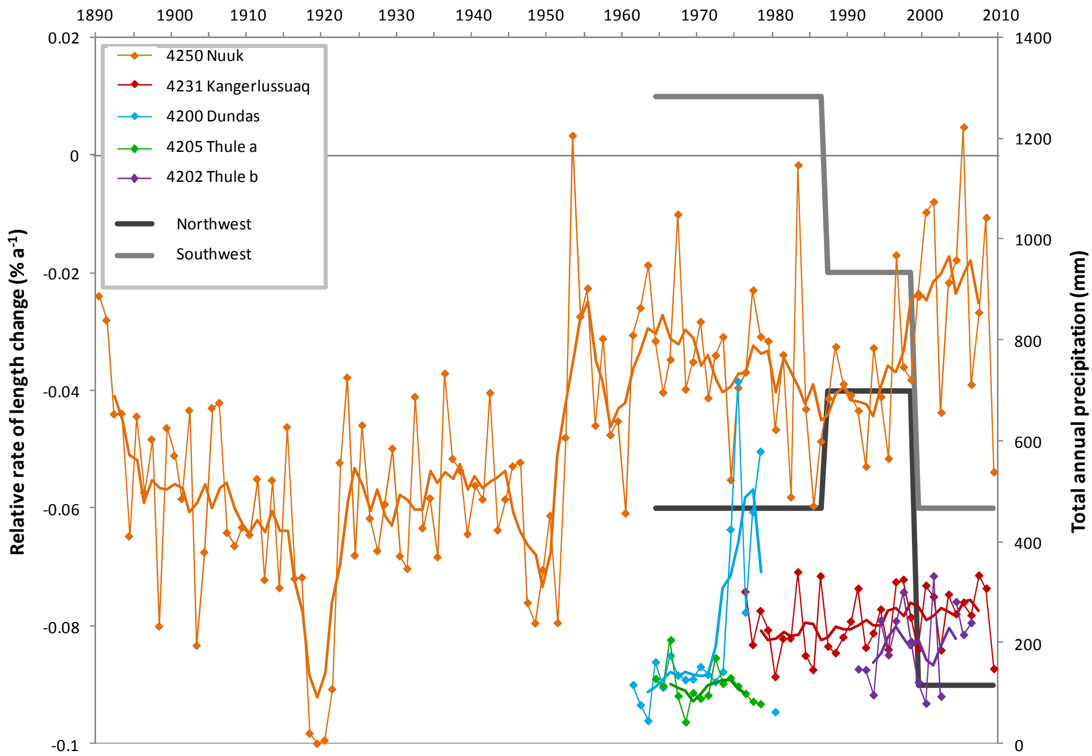


Figure 5.6: Graph showing mean relative rate of glacier length change measured at 4 time steps between 1964 and 2009 (grey lines), and precipitation data (coloured lines), during the twentieth century. Glacier data are based on samples of 33 northwest and 42 southwest glaciers. The solid coloured lines are the 5-year moving averages.

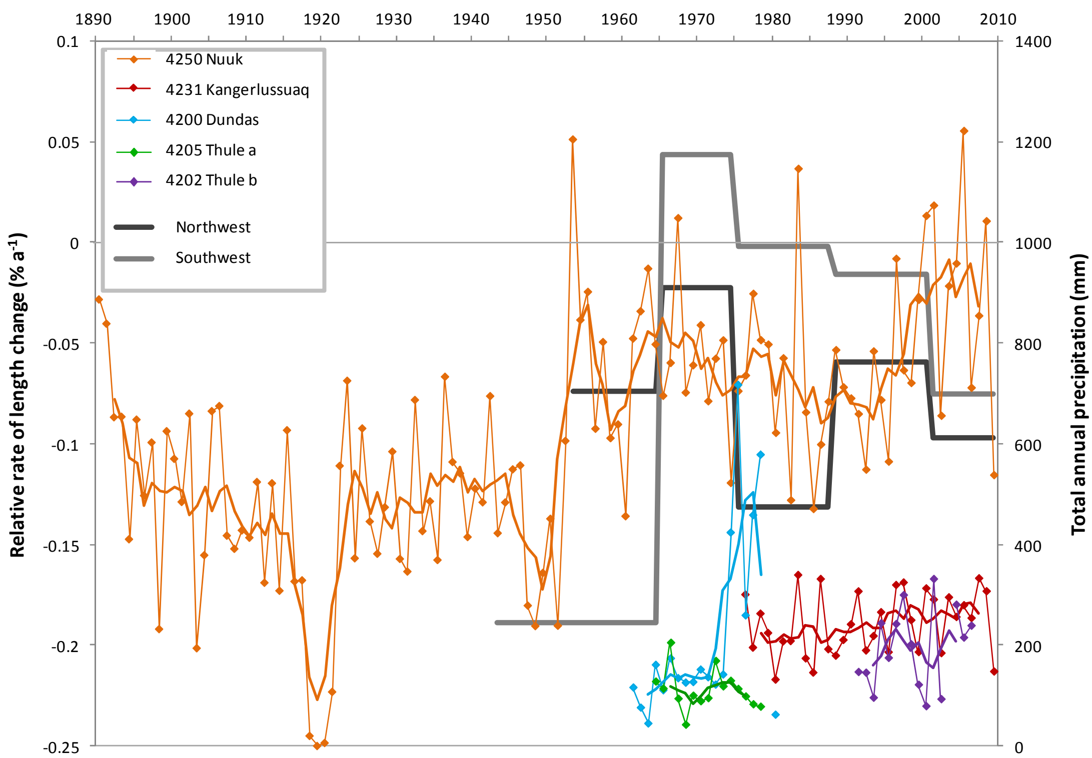


Figure 5.7: Graph showing mean decadal relative rate of glacier length change (grey lines) and precipitation data (coloured lines) during the twentieth century. Glacier data for 1943/53-1964 are based on samples of 8 northwest and 9 southwest glaciers. Data for 1964-2009 are based on 11 northwest and 18 southwest glaciers. The solid coloured lines are the 5-year moving averages.

5.2.5 Summary

In this section, long-term records of air temperature and precipitation from meteorological stations within each study area have been presented. From these data, we can conclude that mean annual temperatures and total precipitation are higher in the southwest than in the northwest. In addition, temperature and precipitation vary considerably within the southwest study area, with both generally higher nearer the coast. No such variation is observed in the northwest study area. It is very hard to assess the extent to which regional climate has influenced glacier behaviour, due partly to errors in the climate data, partly to glaciers being measured at a limited number of time steps, and partly to the very small sample of glaciers that could be measured every decade. However, the data do indicate that there may be some correlation between higher air temperatures and faster glacier retreat in both study areas, particularly during the past two decades. This response suggests a lag time of less than a decade between temperature increases and overall glacier terminus retreat. In addition, the effect of increasing air temperatures on glacier retreat appears to have outweighed the corresponding increase in precipitation in the southwest. In conclusion, whilst it is almost certain that variations in climate have driven some of the observed fluctuations in glacier length, particularly during the past decade, it is impossible to confirm whether there is a significant correlation.

5.3 Rates of length change by class

One of the main aims of this study is to examine the extent to which fluctuations in glacier length are influenced by the class to which it belongs. In Sections 5.3.1 to 5.3.3, variations in rate over time are presented by class for different time periods, and overall length changes of the ice sheet and ice cap margins examined in Section 5.3.4. The spatial patterns of rate change by class are then examined in Section 5.3.5, and the relationship between class and length changes statistically tested in Section 5.3.6, before a summary of the key findings is then given in Section 5.3.7. Table 5.2 gives details of the total number of glaciers in each class for both study areas. A minimum sample size of four glaciers per class is used in the following analyses. The number of glaciers included in every sample is stated in tables and figure captions throughout this chapter.

	Northwest		Southwest	
Class	**Frequency**	**Mean original length (km)**	**Frequency**	**Mean original length (km)**
Ice sheet margin	12	33.0	11	50.0
Ice cap/icefield margin	27	3.3	6	12.3
Ice sheet outlet glacier	37	38.9	47	63.6
Ice cap outlet glacier	37	12.2	72	11.7
Icefield outlet glacier	32	8.5	0	-
Mountain/valley glacier	12	5.8	27	4.4

Table 5.2: Summary statistics for all glaciers measured in each class. See Chapter 3 (Section 3.5.2) for details of how original length was calculated.

5.3.1 Rate changes by class between the LIA and 2009

When rates of length change for all glaciers measured at three time steps between the LIA and 2009 were analysed in Section 4.2.1 (Figure 4.2), they showed that the distance glaciers retreated per year increased over time in the northwest (from -0.09 to -0.01% a^{-1}), whilst the smallest retreat occurred between 1964 and 2001 in the southwest. Relative rates of glacier length change are presented separately for each class in Figure 5.8, and a summary of the data used is given in Table 5.3. The ice sheet margins, ice cap/icefield margins and ice cap, icefield and mountain/valley outlet glaciers in the northwest all match the overall trend of a mean increase in rate over time. The exceptions are the ice sheet outlet glaciers, which retreated very slowly between 1964 and 1999. In the southwest, all classes studied appear to match the overall rate pattern seen in Section 4.2.1, although without data for the LIA-1964 this cannot be confirmed for the mountain glaciers. In addition, glaciers of all classes in the southwest have generally retreated more slowly than those in the northwest, as was observed for the overall trend.

Whilst mean rates of length change for most classes follow a similar overall trend, the magnitude of retreat varies significantly. In the northwest, sections of ice sheet margin have generally retreated the shortest distances at all time periods, whilst the sections of ice cap/icefield margin have retreated the greatest distances relative to their size. Of the outlet glaciers, those draining the ice sheet have retreated the least distance at most time periods, whilst mountain glaciers have retreated the furthest in relative terms. A similar pattern can be observed in the southwest study area, with ice sheet margins and outlet glaciers retreating very short distances, if at all, whilst mountain glaciers have shrunk rapidly relative to their size.

It is interesting to note that individual rates of glacier retreat often vary significantly, and that this within-sample variation tends to increase over time. For example, ice sheet outlet glaciers in the northwest retreated at rates between 0 and -0.13 % a^{-1} from the LIA to 1964, but variation increased to a range of rates between +0.03 and -0.51% a^{-1} from 1999-2009. In some instances the wide range of individual values is partly the result of a few outlying glaciers, which have retreated or advanced significantly further than any others in that class. Particularly good examples of this are the ice cap/icefield margins, four of which retreated large distances between 1999 and 2009. Examination of the dataset shows that these were margins OI002, 0I011, 0I016 and OI018, which are all small independent, land-based icefields. Whilst these margins only retreated a short distance in absolute terms, this equates a large proportion of their overall size.

	Northwest			Southwest		
	LIA-1964	**1964-1999**	**1999-2009**	**LIA-1964**	**1964-2001**	**2001-2009**
Ice sheet margin	0	4	8	0	0	9
Ice cap/ icefield margin	0	4	18	0	0	0
Ice sheet outlet glacier	7	16	27	10	29	37
Ice cap outlet glacier	15	23	30	10	24	52
Icefield outlet glacier	11	11	27	-	-	-
Mountain/ valley glacier	5	6	12	0	5	4

Table 5.3: Number of glaciers in each class measured at each time step and displayed in Figure 5.8 and 5.9.

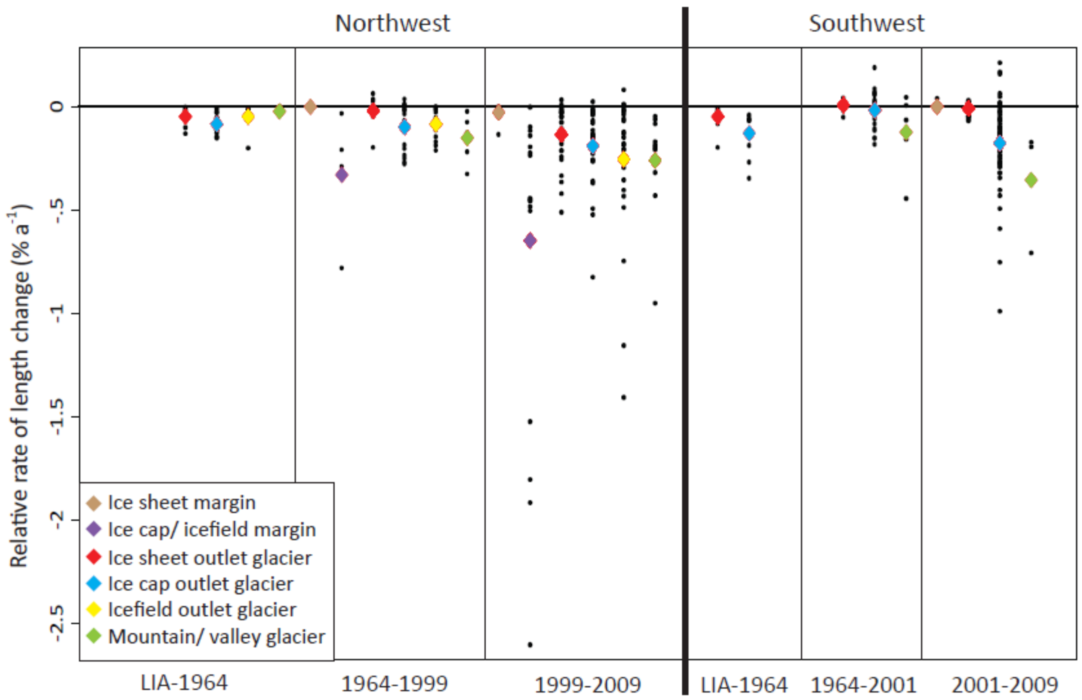


Figure 5.8: Mean and individual relative rates of glacier length change presented for all classes between the LIA and 2009. See Table 5.3 for details of glacier samples used.

Figure 5.9 shows the absolute change of all the glaciers by class. The data for the northwest indicate that ice sheet outlet glaciers have retreated the furthest distances, whilst ice sheet margins have hardly retreated at all. Ice cap, icefield and mountain glaciers have retreated similar absolute distances. This is different to the trend in mean relative rates seen in Figure 5.8, and arises because glaciers of different classes vary in length; ice sheet outlet glaciers are generally very long, so a retreat of several hundred metres only represents a small proportion of their overall length (see Table 5.3). In contrast, mountain glaciers tend to be very short, so a retreat of just 50 metres represents a much more significant percentage of their overall length.

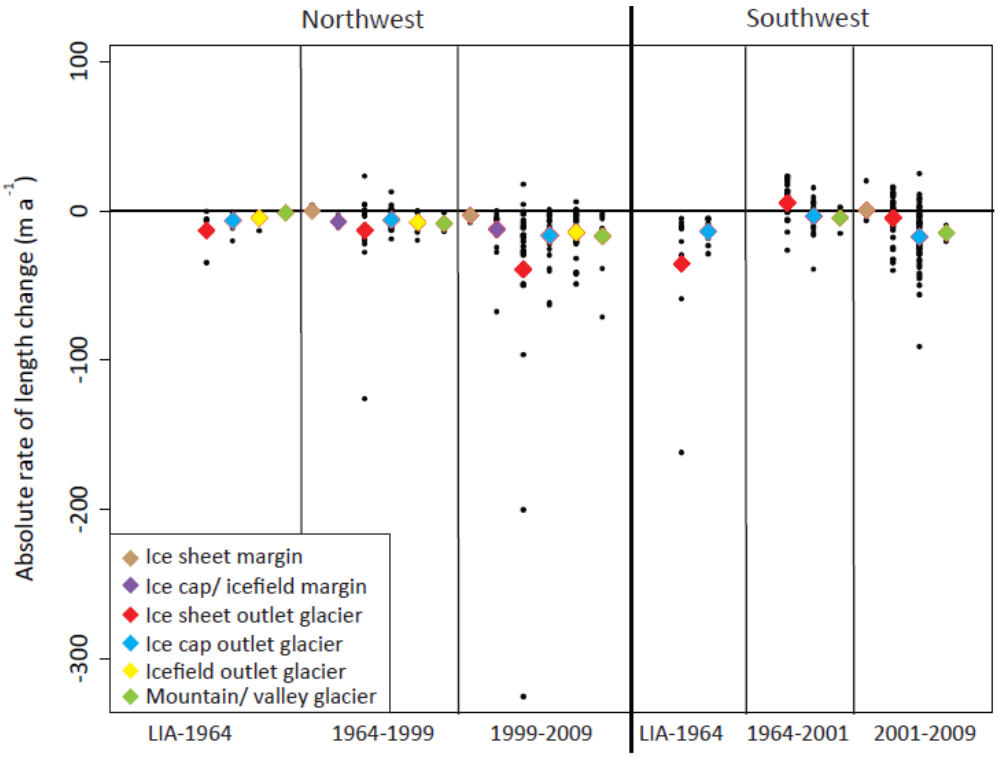


Figure 5.9: Mean and individual absolute rates of glacier length change presented for all classes between the LIA and 2009.

5.3.2 Rates changes by class between 1964 and 2009

When mean rates of length change were calculated for all glaciers measured at four time steps between 1964 and 2009 (Section 4.2.2; Figure 4.4), they indicated that glaciers in the northwest retreated the greatest distances between 1999 and 2009. In the southwest, glaciers advanced overall between 1964 and 1987 and then retreated between 1987 and 2009. A comparison of length changes by class at four time steps from 1964 to 2009 is shown in Figure 5.10, and a summary of the data used is given in Table 5.4. In the northwest, both ice sheet and icefield outlet glaciers follow the overall trend described above, whereas ice cap outlet glaciers retreated most slowly between 1987 and 1999. In the southwest study area, neither the ice sheet nor the ice cap outlet glaciers exactly matched the overall trend shown in Section 4.2.2. The ice cap outlet glaciers advanced between 1964 and 2001, whilst the annual distance retreated by ice cap outlet glaciers increased at all time periods.

	Northwest Number of glaciers	**Southwest** Number of glaciers
Ice sheet margin	0	0
Ice cap/icefield margin	0	0
Ice sheet outlet glacier	10	22
Ice cap outlet glacier	12	13
Icefield outlet glacier	7	-
Mountain/valley glacier	0	0

Table 5.4: Number of glaciers in each class measured at four time steps between 1964 and 2009 and displayed in Figure 5.10.

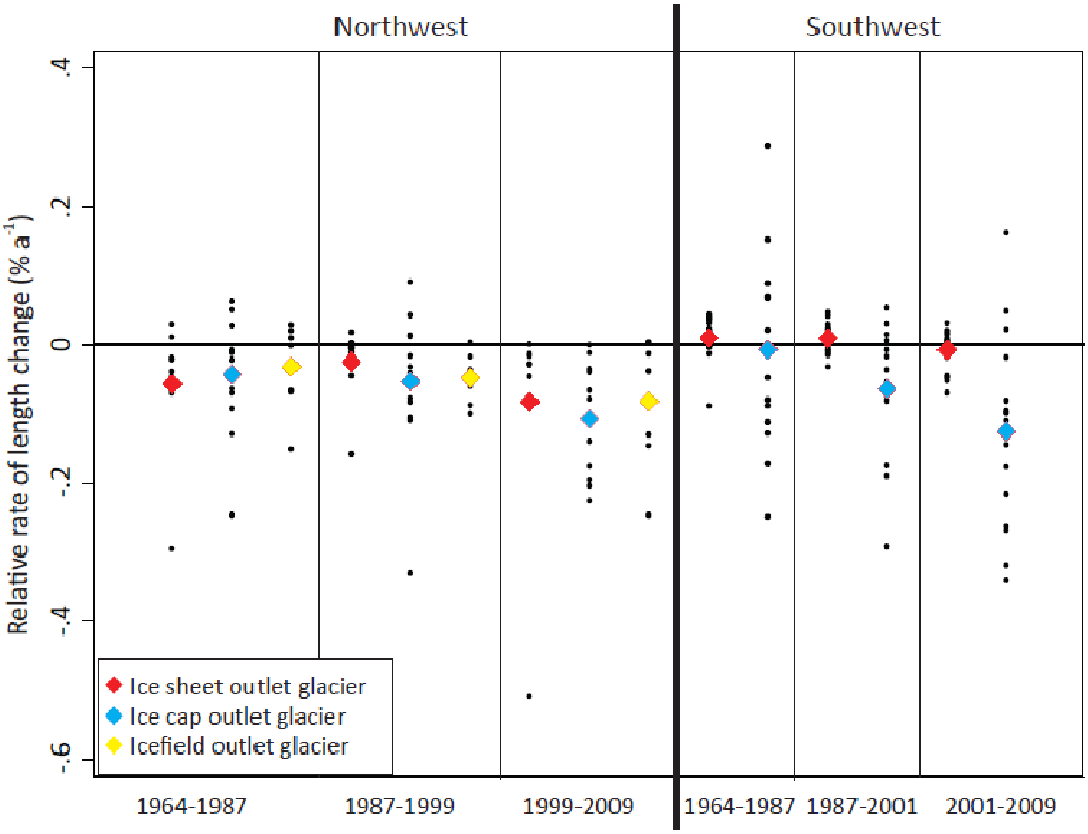


Figure 5.10: Mean and individual relative rates of glacier length change presented for all classes between 1964 and 2009. See Table 5.4 for details of glacier samples.

In general, ice sheet outlet glaciers have retreated shorter relative distances than ice cap or icefield outlet glaciers in both the northwest and southwest study areas, as was shown in Figure 5.8 in the previous section. This is particularly marked in the southwest. Examination of the range of individual rates of length change for each class suggests that ice sheet outlet glaciers in the southwest vary much less within-sample than do ice cap outlet glaciers. The same cannot be said for ice sheet outlet glaciers in the northwest, which have retreated and advanced at very different rates within the same time period. Some of this variation is due to outlying glaciers, and examination of the dataset shows that the glacier that retreated the furthest between 1964 and 1987, and 1999 and 2009 is Glacier 48 (Farquhar Gletscher). Excluding this glacier from the dataset gives slightly slower mean retreat rates for ice sheet outlet glaciers for 1964-1987 and 1999-2009.

5.3.3 Decadal rate changes by class from 1964-2009

Mean rates of length change for all glaciers were calculated at decadal intervals in Section 4.2.3 (Figure 4.5). The results showed that rate of terminus retreat in the northwest had fluctuated, with glaciers retreating shorter distances from 1964-1975 and 1987-1999, and larger distances from 1975-1987 and 1999-2009. In the southwest, glaciers advanced overall from 1964-1973, were stable from 1973-1987 and retreated increasingly larger distances between 1987 and 2009. A comparison of glacier length change data is presented for different classes in Figure 5.11, and details of the glaciers used in each sample are given in Table 5.5. Because only a small number of glaciers could be measured at each decade, not every class is sufficiently represented to be included in the analysis (i.e. four or more glaciers were mapped). In the northwest study area, the trend in mean rates of retreat for ice sheet outlet glaciers matches that observed for all glaciers in Figure 4.5. In the southwest, ice cap outlet glaciers broadly match the overall trend described above, whereas ice sheet outlet glaciers advanced throughout the whole period from 1964-2001 and underwent no net change in length between 2001 and 2009. This is the same pattern as was observed in the previous section, using a larger sample of glaciers (Figure 5.10). As has been observed in the preceding sections, ice sheet outlet glaciers in the northwest have retreated further than those in the southwest.

	Northwest	**Southwest**	
	1964-2009	**1943-1964**	**1964-2009**
Ice sheet margin	0	0	0
Ice cap/ icefield margin	0	0	0
Ice sheet outlet glacier	6	5	8
Ice cap outlet glacier	0	0	8
Icefield outlet glacier	0	-	-
Mountain/ valley glacier	0	0	0

Table 5.5: Number of glaciers in each class measured at decadal intervals between 1943/53 and 2009 and displayed in Figure 5.11.

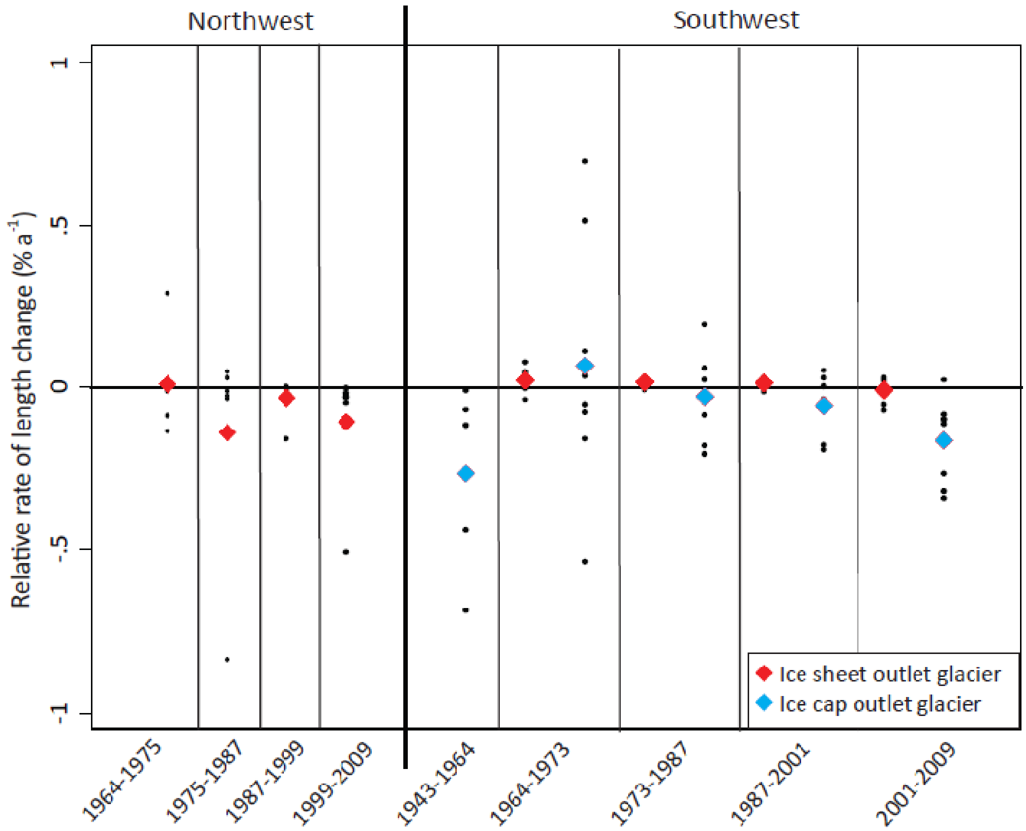


Figure 5.11: Mean and individual relative rates of glacier length change presented for all classes at decadal intervals between 1964 and 2009. See Table 5.5 for details of glacier samples. Note that data for 1943-1964 in the southwest are based on a different sample of glaciers to data for all other time periods.

Examination of the individual rates of change indicates that there are some outlying glaciers within the ice sheet outlet glacier sample for the northwest. Examination of the original data confirms that this is once again due to Glacier 48 (Farquhar), which advanced further than any other in the sample between 1964 and 1975, and then retreated significantly greater distances from 1975-1987 and 1999-2009. If this glacier is excluded from the dataset the overall pattern of mean retreat stays the same, but is more muted. In the southwest, the within-sample variance of ice sheet outlet glaciers is much smaller than that of the ice cap outlet glaciers and northwest ice sheet glaciers. This is the same pattern as has been observed in earlier sections of the class analysis.

5.3.4 Ice sheet and ice cap margins

During the mapping process, it was found that the ice sheet and ice cap margins in both the northwest and southwest study areas were often partially obscured by snow cover, making them difficult to delineate. Often, only a few sections of margin could be mapped at any one particular year, so they have had to be excluded from the general analysis above. In order to investigate their behaviour more fully, graphs of cumulative absolute length relative to margin positions in 1975 (northwest) and 1987 (southwest) are shown in Figures 5.12 and 5.13. These samples comprise 4 ice cap margins and 12 ice sheet margins in the southwest, and 4 ice cap margins and 9 ice sheet margins in the northwest.

The data for the northwest indicates that the ice sheet margins have undergone no significant net change in terminus position overall between 1975 and 2009, although there are two sections of margin that have retreated further than any others. The mean cumulative length change of the ice cap margins has fluctuated more than that of the ice sheets, and they have retreated further overall, but the distance retreated varies significantly between individual margins. Measurements of more ice cap margins are required to give a better picture of overall behaviour in this region.

In the southwest, the ice sheet margins have advanced continuously very slowly between 1987 and 2009. Only three sections of margin have retreated any significant distance overall. In contrast, ice cap margins have undergone mean cumulative retreat since 1987 and none have advanced overall, although one section underwent no net change in length. As in the northwest, more ice cap measurements are required to investigate this trend.

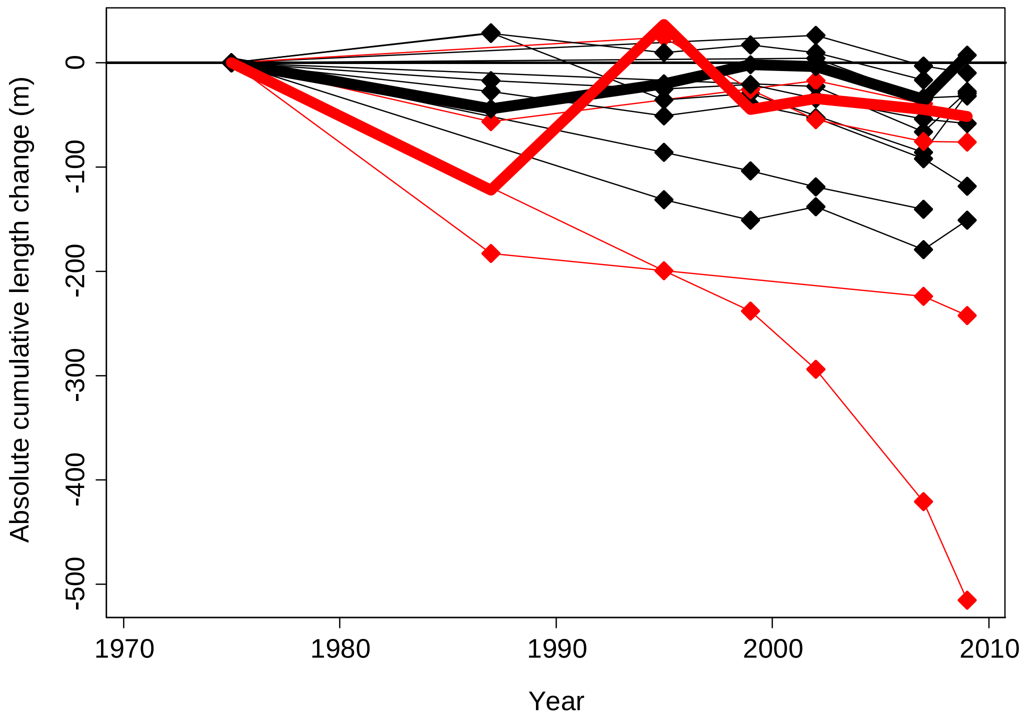


Figure 5.12: Absolute cumulative length changes in the northwest of 9 sections of ice sheet margin (black) and 4 sections of ice cap margin (red) relative to their position in 1975. The bold lines show mean cumulative change for each class.

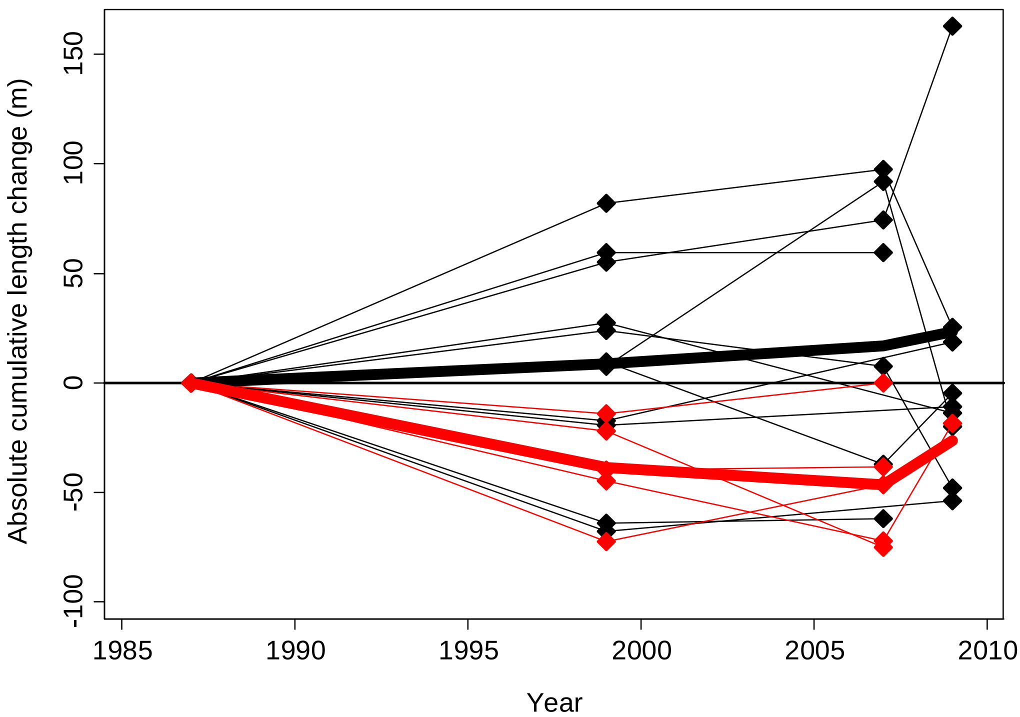


Figure 5.13: Absolute cumulative length changes in the southwest of 11 sections of ice sheet margin (black) and 4 sections of ice cap margin (red) relative to their position in 1987. The bold lines show mean cumulative change for each class.

5.3.5 Spatial patterns of glacier length changes, by class

In order to examine as the spatial change of as many glaciers as possible over the longest time period, separate samples of glaciers measured between 1964 and 1999/2001, and 1999/2001 and 2009, are used. Before examining spatial patterns of length change, the sample glaciers in each study area were first sorted into bins, based on their mean relative rate of length change per year from 1964-1999/2001 and 1999/2001-2009. The majority of glaciers had a mean length change rate of between +0.2% advance and -0.5% retreat per year. An arbitrary bin width of 0.1% a^{-1} was therefore used. The maps of spatial change by class in the northwest are shown in Figures 5.14 and 5.15, and those for the southwest in Figures 5.16 and 5.17.

The maps of spatial change highlight patterns of glacier behaviour that cannot be identified from graphs. In particular, they show that neighbouring glaciers can behave very differently, even if they are of the same class. For example, all of the glaciers draining ice cap ‘A’ in Figure 5.15 are ice cap outlets, yet they retreated at very different rates between 1999 and 2009. Similar examples can be seen throughout the northwest and southwest study areas, and are probably a consequence of differences between glacier terminus environments, or other characteristics such as length and aspect.

The spatial maps are also a useful tool for examining whether glaciers in any particular area of each region have retreated significantly longer or shorter distances than the rest. The maps for the northwest indicate that glaciers around Granville Fjord (location ‘B’, Figure 5.15) retreated at relatively large distances compared to most other independent glaciers in the region between 1999 and 2009, although individual glaciers had retreated at similar rates in other parts of the study area. In the southwest, the ice sheet outlet glaciers draining the southern sector of the ice margin, surrounding glacier 1CH 23 003 (Kangiata nunata sermia; location ‘C’, Figure 5.16) retreated from 1964-2001, whilst the rest of margin advanced. Between 2001 and 2009, however, they retreated at a similar rate to many other ice sheet outlet glaciers. Rates of retreat for the independent glaciers were uniformly varied at both time periods, with no one area retreating at particularly large or short distances.

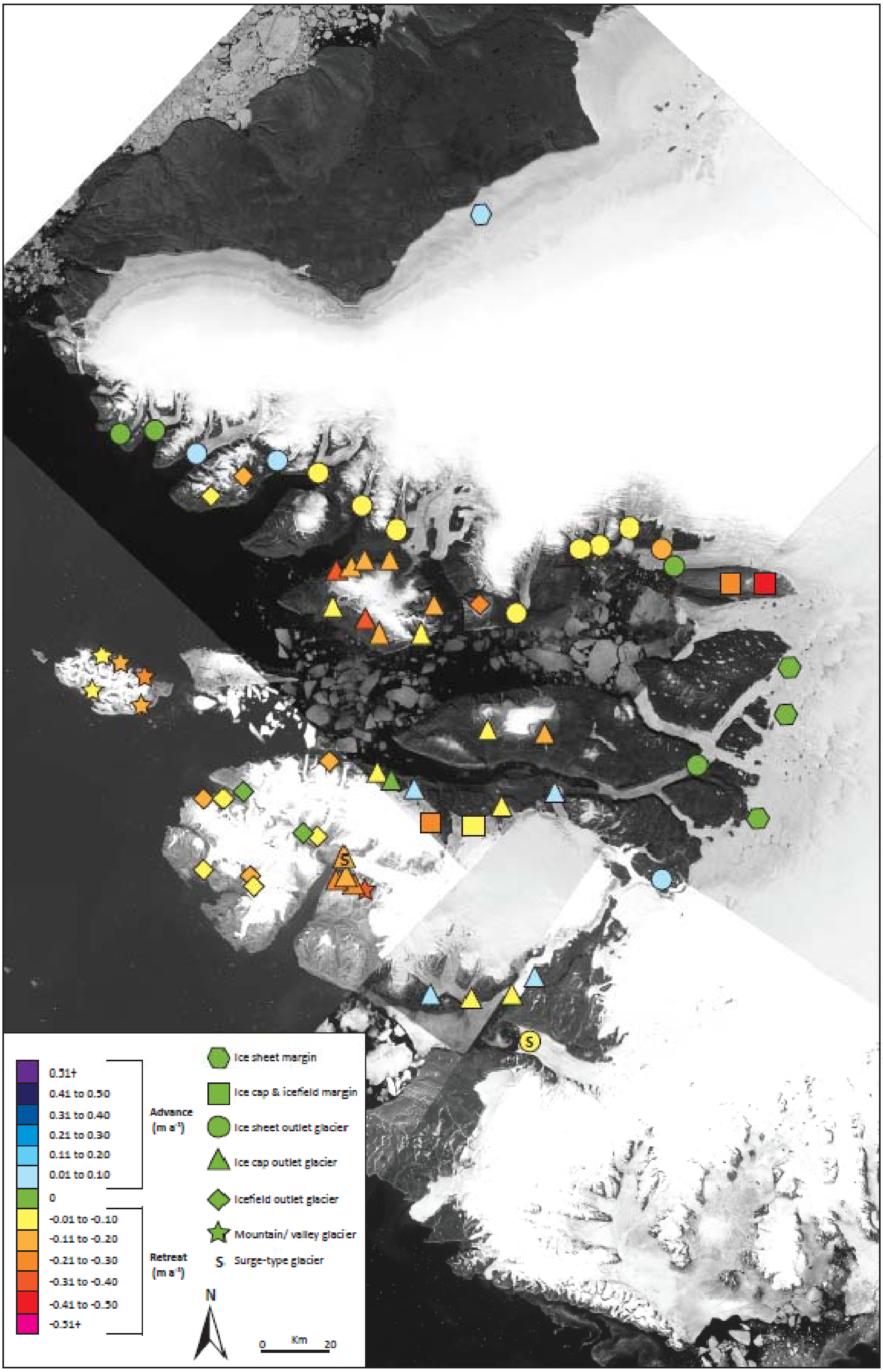


Figure 5.14: Relative length change data for all glaciers measured between 1964 and 1999 in the northwest study area. The symbols refer to the different glacier classes, and the colours to rate of length change. Background is the 1999 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

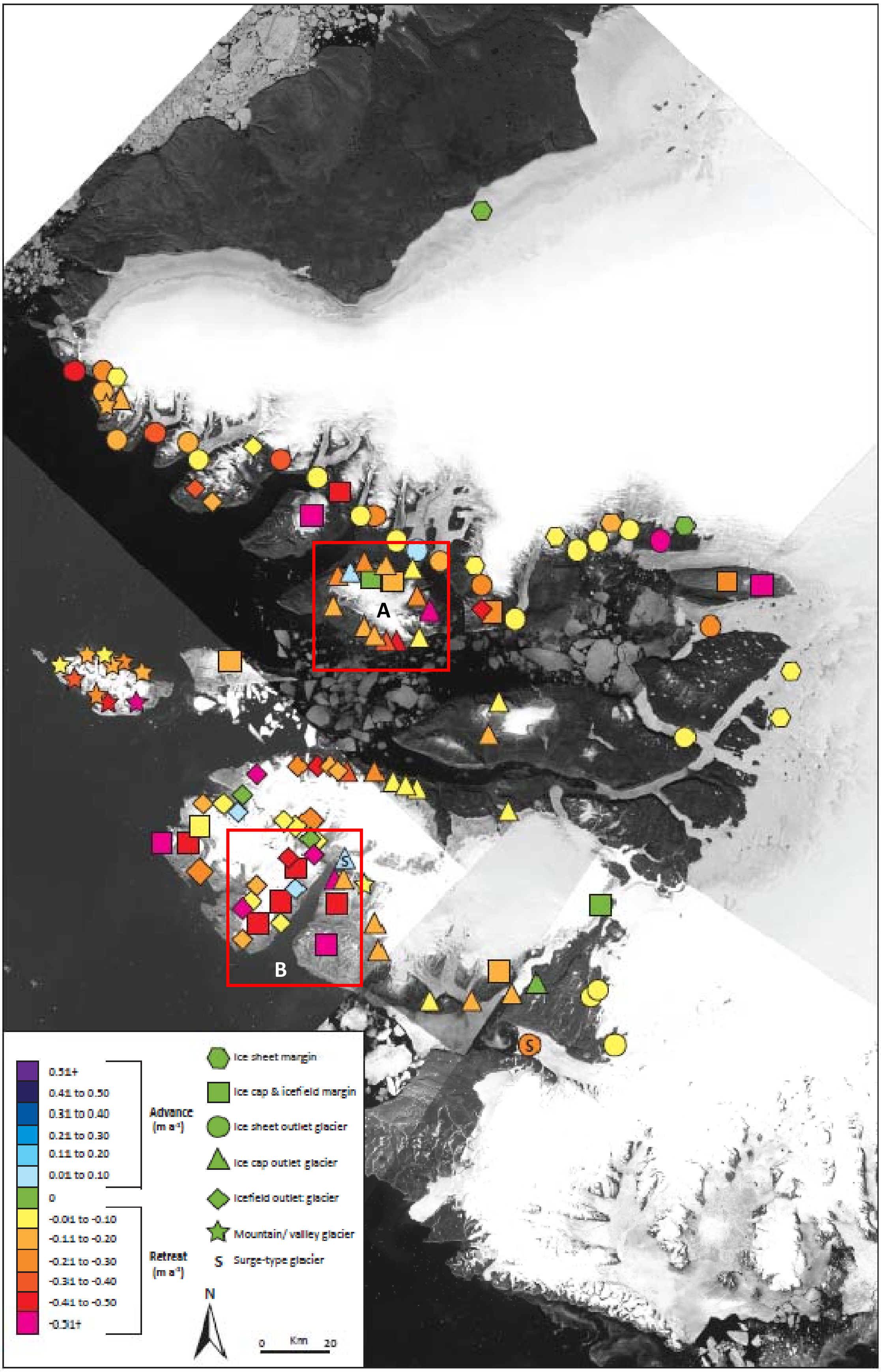


Figure 5.15: Relative length change data for all glaciers measured between 1999 and 2009 in the northwest study area See text for description of locations A and B. Background is the 1999 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

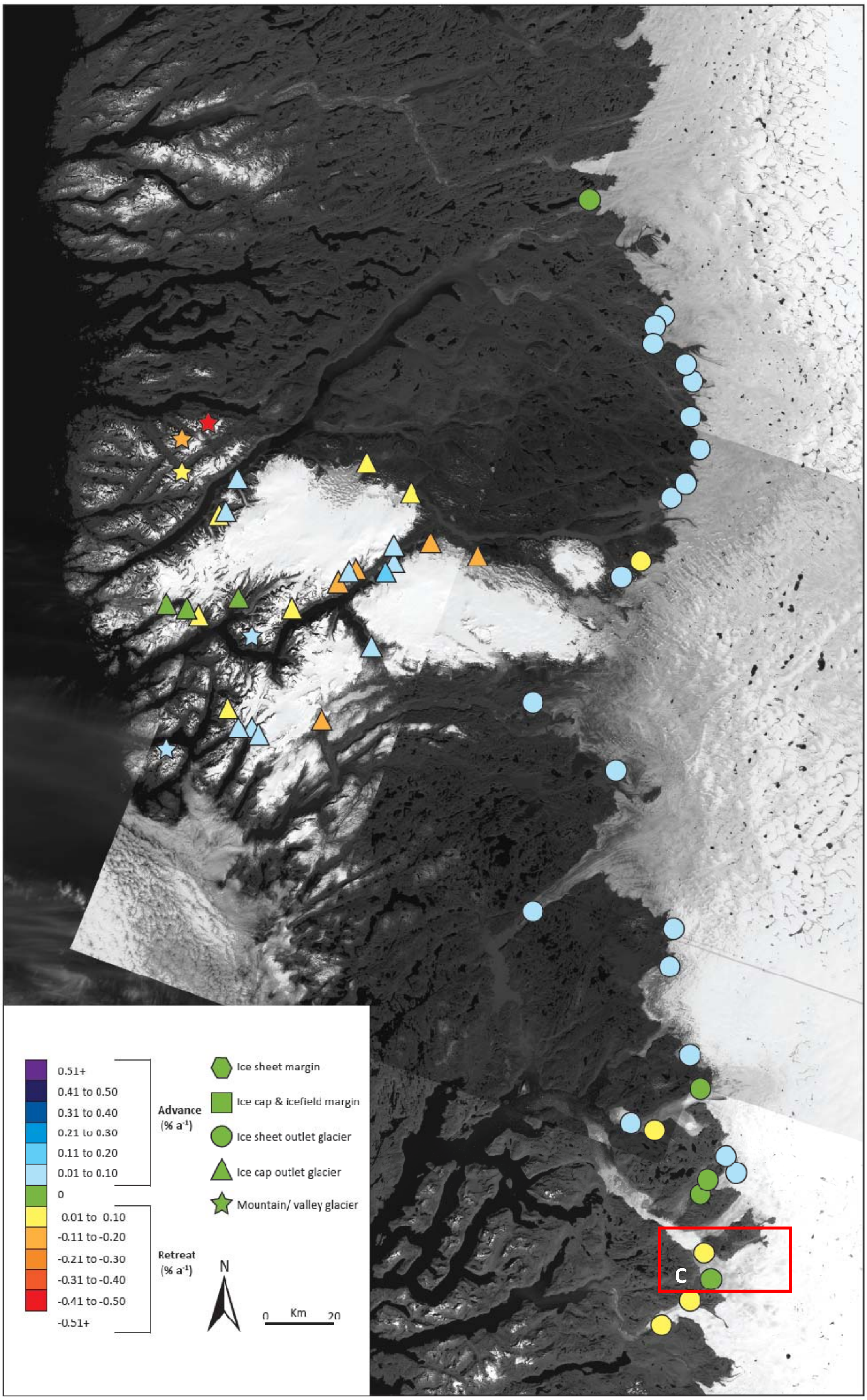


Figure 5.16: Relative length change data for all glaciers measured between 1964 and 2001 in the southwest study area. See text for description of location C. Background is the 2001 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

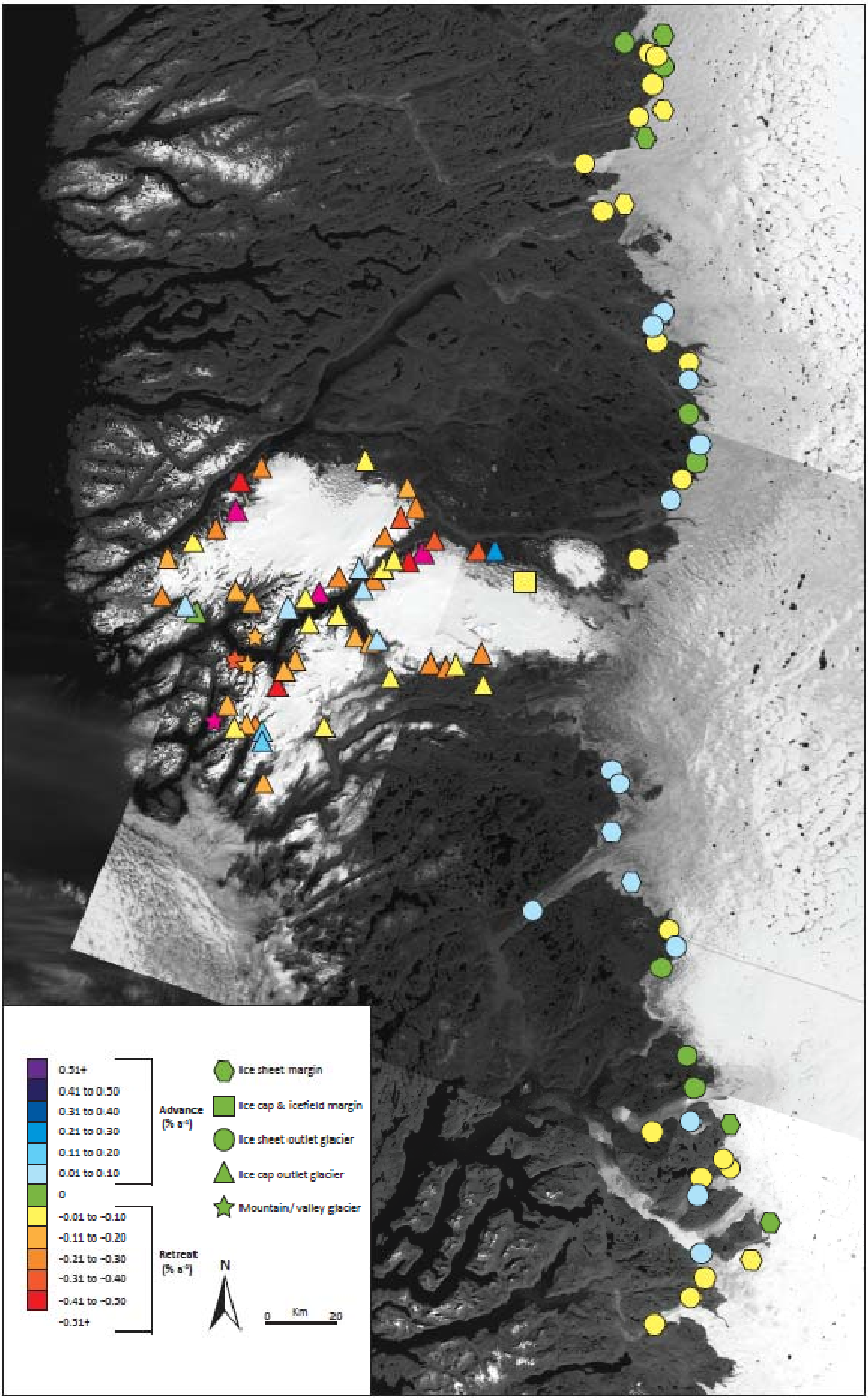


Figure 5.17: Relative length change data for all glaciers measured between 2001 and 2009 in the southwest study area. Background is the 2001 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

5.3.6 Testing the relationship between class and length changes

One-way ANOVA tests can be used to determine whether glacier of different classes have retreated different distances over time, relative to their overall length. They are a useful tool for determining whether the mean values of two or more groups are similar or significantly different. This analysis will be undertaken on the sample of glaciers measured at 1964 and 1999/2001, and as explained in Chapter 3 (Section 3.5.5) the un-transformed data will be used throughout.

The one-way ANOVA test give a p-values of 0.0003 in the northwest and $p=0.0044$ for the southwest. Both values fall within the 95 % confidence interval ($p<0.05$), so glacier class had a significant influence on the relative rate of glacier length change between 1964 and 1999/2001. However, these results do not tell us whether there is a difference between all the classes, or just between some classes. A Bonferroni multiple-comparison test was used, in conjunction with ANOVA, to test whether there is a difference between all categories. For the northwest study area, the results showed that only some classes have statistically different mean rates of retreat, whereas the others are not statistically different (see Table 5.6). It would appear that there are statistical differences between mean rates of retreat of the ice sheet outlets and margins and the ice cap margins/mountain glaciers, but not between the different types of independent glacier. In the southwest only three glacier classes were tested (ice sheet outlet, ice cap outlet and mountain glaciers), and the Bonferroni test indicated that ice sheet and ice cap outlets do not have statistically different mean rates of length change, but that both are different to mountain glaciers (Table 5.7). From these results we can conclude that whilst in general class has a significant influence on glacier length change, many classes have similar rates.

	Ice sheet outlet glaciers	Icefield outlet glaciers	Ice cap/ icefield margins	Mountain/ valley glaciers	Ice cap outlet glaciers
Icefield outlet glaciers	0.901				
Ice cap/ icefield margins	0.001	0.057			
Mountain/ valley glaciers	0.042	1.000	1.000		
Ice cap outlet glaciers	0.122	1.000	0.076	1.000	
Ice sheet margins	1.000	1.000	0.005	0.161	0.703

Table 5.6: Results of the Bonferroni multiple-comparison test for difference between mean rates of relative length change of different classes in the northwest. Results that fall within the 95 % confidence interval (<0.05) are highlighted in yellow.

	Ice sheet outlet glaciers	Mountain/ valley glaciers
Mountain/ valley glaciers	0.003	
Ice cap outlet glaciers	0.838	0.022

Table 5.7: Results of the Bonferroni multiple-comparison test for difference between mean rates of relative length change of different classes in the southwest. Results that fall within the 95 % confidence interval (<0.05) are highlighted in yellow.

5.3.7 Summary

The data presented in Section 5.2 indicate that glaciers of all classes, in both the northwest and southwest, retreated overall between the Little Ice Age and 2009, and that the distance retreated per year has increased over time for most classes. However, it is also clear that the timing and magnitude of retreat varies by class, with ice sheet outlet glaciers and margins generally retreating shorter distances as a proportion of their length than ice cap/icefield margins and ice cap, icefield and mountain outlet glaciers. The opposite trend is seen when absolute length change data for the northwest are examined, with ice sheet outlet glaciers retreating greater distances than ice cap, icefield or mountain glaciers. Ice sheet margins do not retreat significantly in either relative or absolute terms. Ice sheet outlet glaciers advanced overall between 1964 and 1999/2001 in the southwest, contrary to the mean retreat observed in the northwest. In addition, whilst ice cap outlets and mountain glaciers in the southwest have retreated throughout the majority of the twentieth century, the mean annual distance has generally been smaller than in the northwest.

5.4 Rates of length change by terminus environment

The type of terminus environment is known to be a significant factor in determining the timing and extent of glacier response to climate change (Warren, 1991). One of the aims of this study is to investigate the effect that terminus environment has had on glacier fluctuations in the northwest and southwest study areas during the twentieth century. In Sections 5.4.1 to 5.4.3 variations in length change are presented separately for glaciers with different terminus environments over several different time periods. The spatial variation of rate changes of glaciers with different terminus environments is examined in Section 5.4.4 and the relationship between terminus environment and length change statistically tested in Section 5.4.5. A summary of the key findings is given in Section 5.4.6. Table 5.8 gives details of the total number of glaciers by terminus environment for both study areas.

	Northwest			Southwest		
Terminus environment	**Frequency**	**Number of glaciers as percentage of total**	**Mean original length (km)**	**Frequency**	**Number of glaciers as percentage of total**	**Mean original length (km)**
Lake	2	1	20.8	14	9	40.1
Land	117	75	10.9	109	67	26.7
Land/lake	3	2	34.6	7	4	62.9
Tidewater	35	22	36.2	33	20	18.5

Table 5.8: Summary statistics for all glaciers, classed by their terminus environment. The land/lake category refers to glaciers that terminate partially in a lake and partially on land (see Chapter 3, Section 3.5.3).

5.4.1 Rate changes by terminus environment between the LIA and 2009

Glaciers in the northwest retreated overall between the LIA and 2009, and annual distance retreated increased over time (see Chapter 4, Section 4.2.1). In the southwest glaciers also retreated throughout this time period, but the mean rate of length change was smallest between 1964 and 2001. A comparison of glacier length change data is presented for different terminus environments in Figure 5.18, and details of the glaciers are given in Table 5.9. In the northwest, both land and tidewater terminating glaciers follow the same overall trend described in Section 4.2.1, but land glaciers have undergone the largest increase in mean distance retreated per year. The data for individual rates of glacier retreat indicates that 10 land-terminating glaciers retreated much further than the other 78 glaciers measured between 1999 and 2009. The four glaciers that underwent the most retreat are ice cap/icefield margins, and the six other glaciers are all small ice cap outlets, icefield outlets or mountain glaciers located in different regions of the study area.

In the southwest, both land and tidewater glaciers match the overall trend described in Section 4.2.1, of least retreat between 1964 and 2001. Unlike in the northwest, they have retreated at very similar mean relative rates during each time period. In contrast, the lake and land/lake-terminating glaciers appear to have retreated shorter distances, particularly between 1999 and 2009. Indeed, land/lake glaciers show no signs of mean retreat at any time period. There are no obvious outliers in any of the southwest terminus classes, but it would appear that land-terminating glaciers have the most within-sample variance, and land/lake glaciers the least. However, this is probably at least partially due to more land glaciers having been measured than any other type (see Table 5.8).

It is interesting to compare these results to absolute glacier length changes for each type of terminus environment (Figure 5.19). In the northwest, the trend seen in Figure 5.18 is reversed, with land-terminating glaciers retreating shorter distances than tidewater glaciers at all time steps. However, because the tidewater glaciers are on average longer than the land glaciers this length change does not equate to such a significant proportion of their total length. The two tidewater glaciers that have retreated the greatest distance in terms of absolute length are ice sheet outlet Glaciers 48 (Farquhar Gletscher) and 50 (Heilprin Gletscher). The rapid retreat of Glacier 48 has been discussed in previous sections, and Glacier 50 is located nearby. In the southwest, the mean rate of absolute retreat of tidewater glaciers appears to be strongly influenced by Glacier 1CH 23 003a (Kangiata nunata sermia), which retreated by 161 metres between the LIA and 1964. This glacier was previously observed to have retreated further than any other measured in the overall sample in Section 4.2.1.

	Northwest			Southwest		
	LIA-1964	1964-1999	1999-2009	LIA-1964	1964-2001	2001-2009
Lake	0	0	0	0	7	12
Land	26	43	90	14	32	62
Land/lake	0	0	0	0	6	7
Tidewater	11	20	29	4	13	22

Table 5.9: Number of glaciers of each terminus environment measured at each time step between the LIA and 2009 and displayed in Figure 5.18 and 5.19.

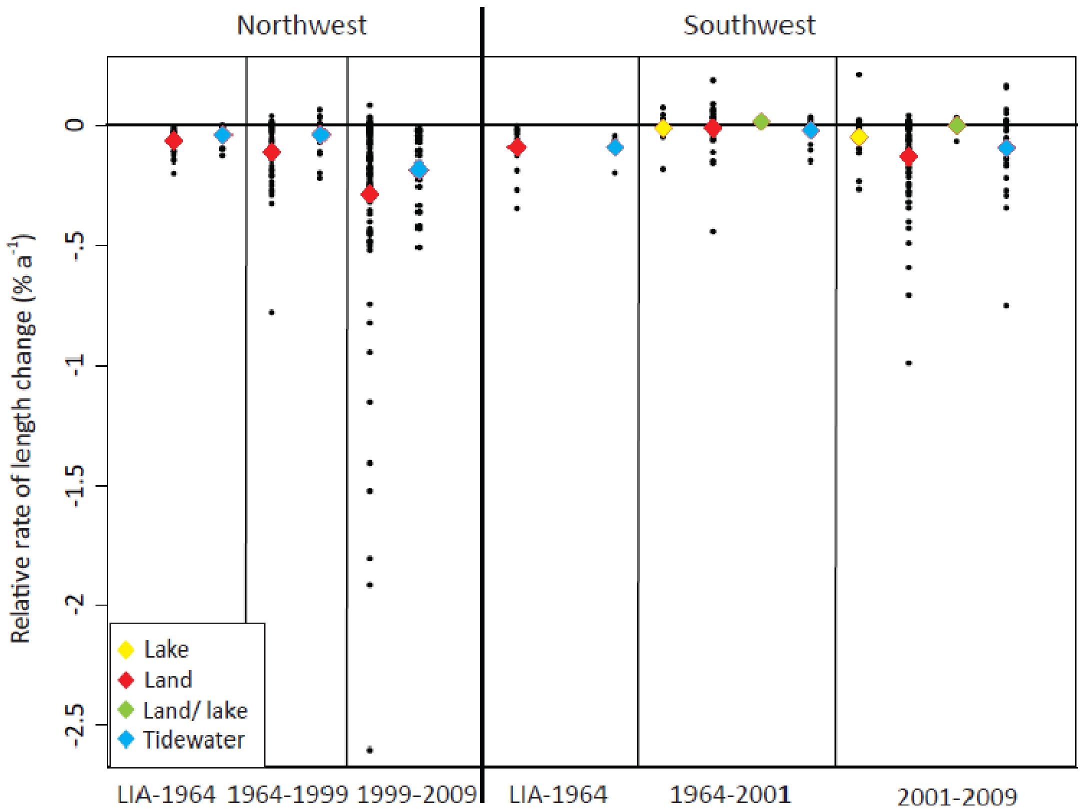


Figure 5.18: Mean and individual relative rates of length change for glaciers with all terminus environments from the LIA to 2009. See Table 5.9 for details of sample sizes. Note that results for each time step are calculated from separate samples.

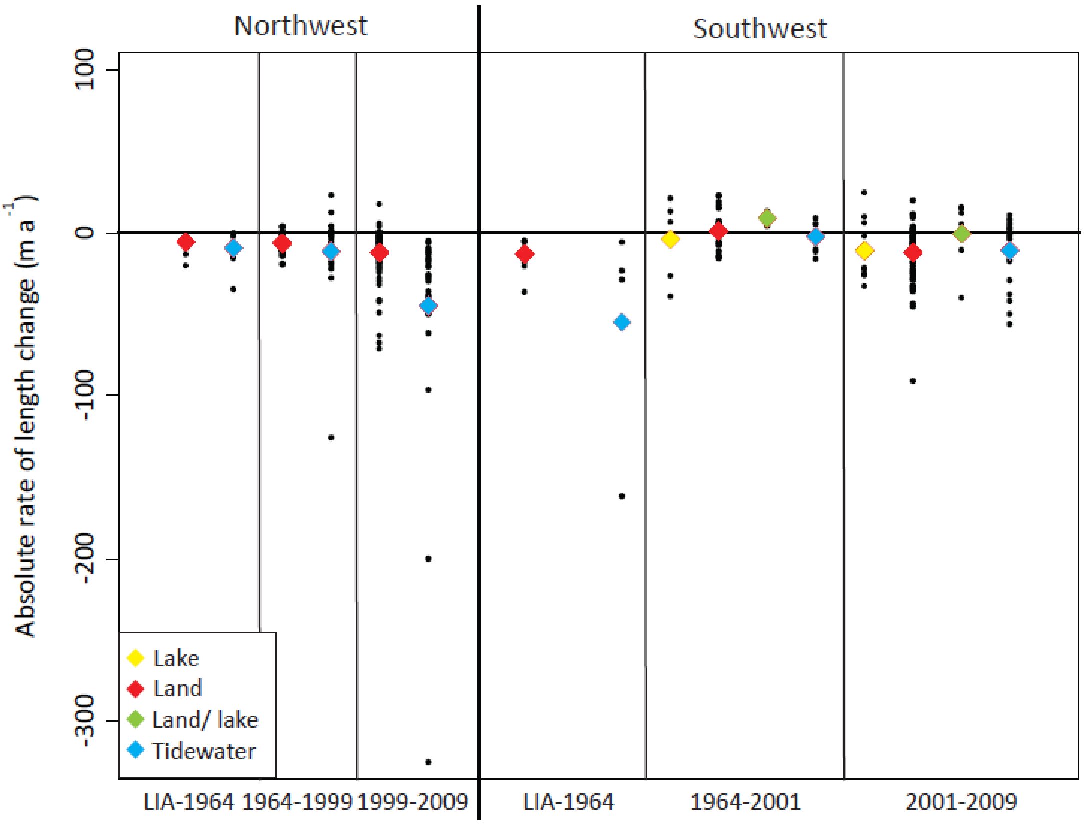


Figure 5.19: Mean and individual absolute rates of length change for glaciers with different terminus environments from the LIA to 2009, for the glaciers shown in Figure 5.18 and Table 5.9.

5.4.2 Rates changes by terminus environment from 1964- 2009

When rates of length change for all glaciers measured at four time steps between 1964 and 2009 were calculated (Section 4.2.2), they indicated that glaciers in the northwest had retreated overall throughout the whole period, at a steady annual rate from 1964-1987 and then larger distances from 1999-2009. In the southwest, no significant change in mean length occurred between 1964 and 1987, followed by overall glacier retreat between 1987 and 2009, with distance retreated increasing over time. Relative rates of length change between 1964 and 2009 for glaciers with different terminus environments are shown in Figure 5.20, and details of the glacier samples used are given in Table 5.10. The results for the northwest show that neither land-terminating nor tidewater glaciers have followed the overall trend described above. Land-terminating glaciers began retreating greater distances between 1987 and 1999, whilst tidewater glaciers retreated very short distances from 1987-1999 and very large distances from 1999-2009. The data points of length change for each individual glacier indicate a similar extent of within-sample variance for both land and tidewater terminating glaciers at all time periods. In addition, some glaciers have retreated much further than the majority, most notably tidewater terminating ice sheet outlet Glacier 48 (Farquhar) and land-terminating ice cap outlet Glacier 33, which retreated further than most other glaciers in this sample at all time steps.

	Northwest Number of glaciers	**Southwest** Number of glaciers
Lake	0	6
Land	17	19
Land/lake	0	5
Tidewater	13	5

Table 5.10: Number of glaciers of each terminus environment measured at four time steps between 1964 and 2009 and displayed in Figure 5.20.

In the southwest, lake-terminating glaciers match the overall trend described for all glaciers in Section 4.2.2 of no net change from 1964-1987, following by increasing retreat. Land-terminating glaciers show a similar pattern, with mean advance 1964-1987 followed by retreat at later periods, whereas land/lake-terminating glaciers advanced between 1964 and 2001 and underwent no change in mean length from 2001-2009. In contrast, tidewater glaciers have retreated at all time steps. These results are not inconsistent with those shown in Figure 5.18 in the previous section. The data for individual glaciers indicate that land-terminating and tidewater glaciers experience similar levels of within-sample variance, whilst lake and land/lake-terminating glaciers have much less variation, possibly due to fewer such glaciers having been measured. Glaciers of all terminus environments in the southwest have retreat smaller distances than glaciers in the northwest during all time periods. In addition, land-terminating and tidewater glaciers in the southwest retreated similar relative distances between 1987 and 2009, unlike their counterparts in the northwest.

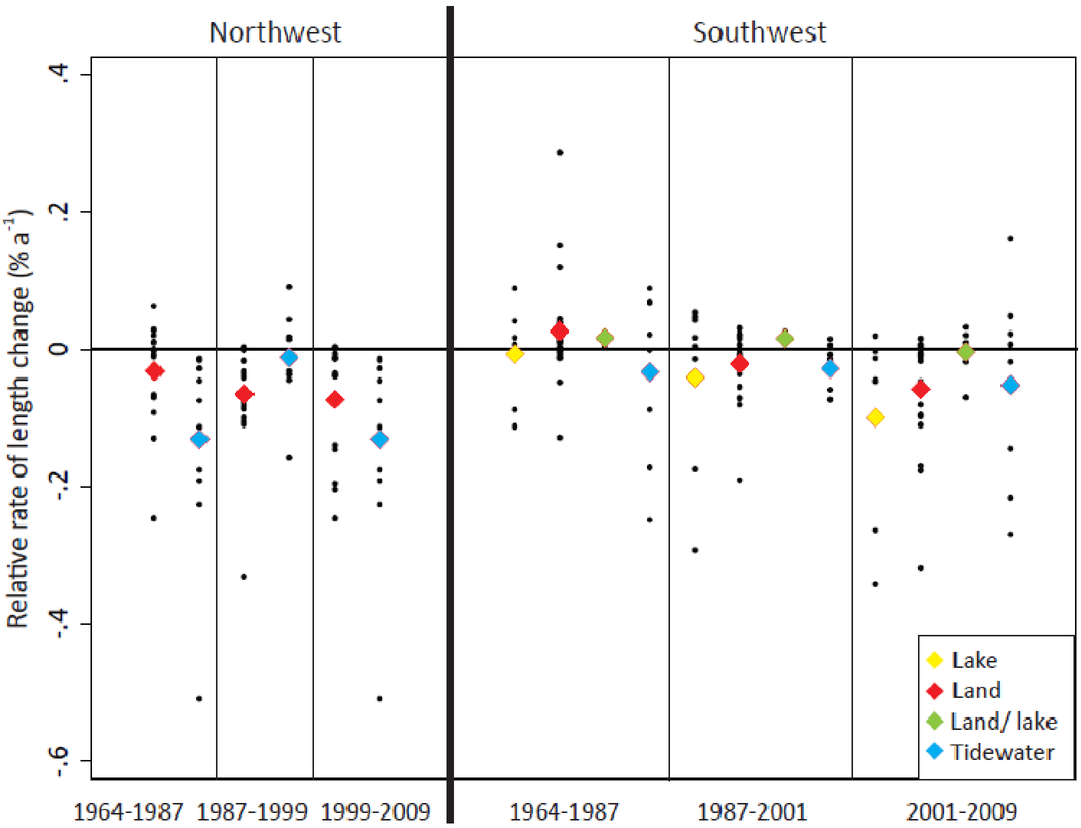


Figure 5.20: Mean and individual relative rates of length change for glaciers with all terminus environments from 1964 to 2009. See Table 5.10 for details of sample sizes.

5.4.3 Decadal rate changes by terminus environment

When decadal rates were originally calculated for all glaciers in the northwest (see Section 4.2.3, Figure 4.5), they fluctuated between large and small mean retreat distances each decade, with smallest length changes between 1964-1975 and 1987-1999. In the southwest, a mean advance occurred from 1964-1975, followed by no mean change between 1975 and 1987 and increasing retreat thereafter. A comparison of decadal rates by terminus environment is shown in Figure 5.21, with details of the data samples given in Table 5.11. In the northwest, only tidewater glaciers match the overall trend described above, with slight advance/limited retreat from 1964-1975 and 1987-1999, and more significant retreat from 1975-1987 and 1999-2009. In contrast, land-terminating glaciers retreated at a relatively steady rate throughout the whole time period. In Section 4.2.3 it was observed that fluctuations in mean retreat rates for all glaciers partly reflect the fluctuations of Glacier 48 (Farquhar), which advanced large distances from 1964-1975 and retreated significant distances from 1975-1987 and 1999-2009. These relative length changes are significantly larger than those observed for any other tidewater terminating glacier during this period, particularly between 1975 and 1987. Excluding it from the dataset gives a mean rate of retreat of 0% for the four other glaciers sampled. This is significantly lower than the mean rate shown in Figure 5.21, and results in a pattern of a steady increase in distance retreated per year over time. However, with measurements for so few tidewater glaciers it is impossible to determine which trend is a more realistic representation of glacier behaviour in this study area.

	Northwest		**Southwest**	
	1953-1964	**1964-2009**	**1943-1964**	**1964-2009**
Lake	0	0	0	0
Land	5	6	5	10
Land/lake	0	0	0	4
Tidewater	0	5	0	0

Table 5.11: Number of glaciers of each terminus environment measured at decadal intervals between 1943/53 and 2009 and displayed in Figure 5.21.

Data for the southwest study area suggest that land-terminating glaciers advanced from 1964-1973 and retreated thereafter, whereas land/lake-terminating glaciers show either no net change in length or slight mean advance during all decades. These trends are consistent with those observed in the previous two sections. The individual data points show that all land/lake-terminating glaciers have changed in length by similar amounts each year, relative to their overall length. Land-terminating glaciers have greater variance, and some glaciers have advanced or retreated further than others. Most notably, ice cap outlet Glaciers 1DF 16 009 and 1DF 16 246 retreated further than any others in all three time periods between 1973 and 2009. It is unclear why this has occurred.

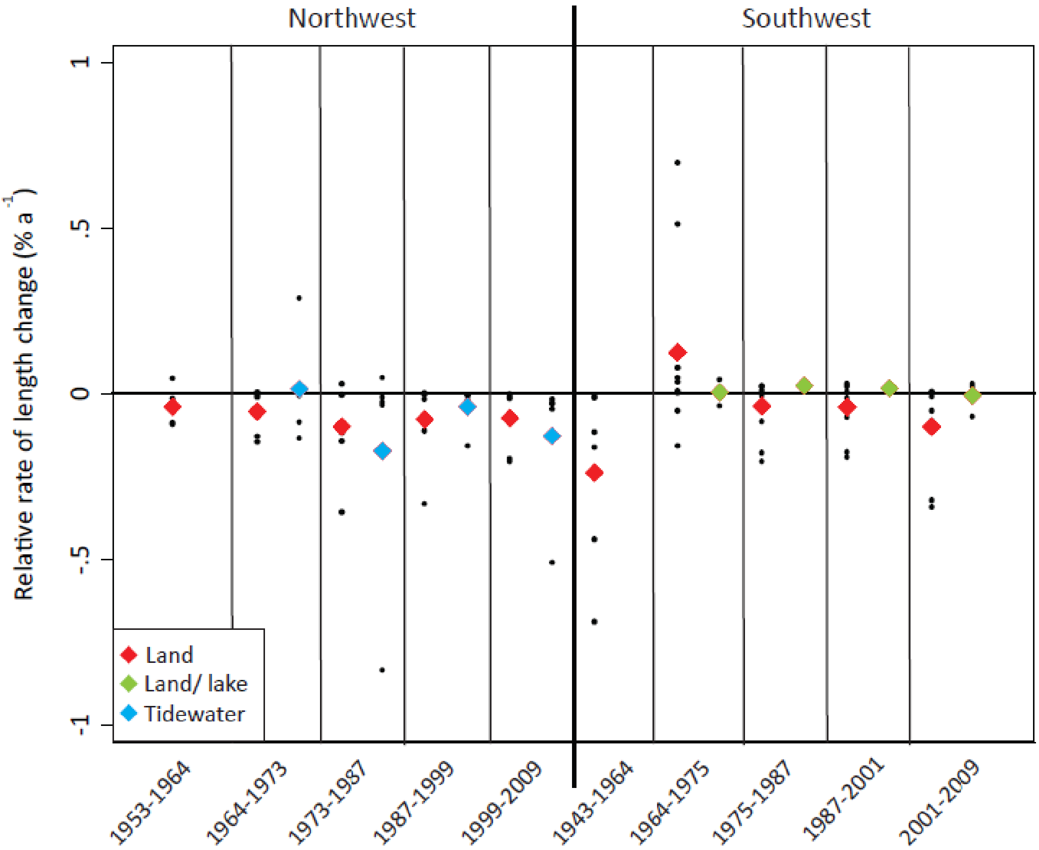


Figure 5.21: Mean and individual relative rates of length change for glaciers of all terminus environments measured at decadal intervals. See Table 5.11 for details of sample sizes.

5.4.4 Spatial patterns of glacier length changes, by terminus environment

The maps illustrating the spatial patterns of relative glacier retreat by class presented in Section 5.2.4 indicated that neighbouring glaciers of the same class had often retreated at very different rates. In this section, maps showing spatial patterns of relative rate of length change by terminus environment are presented, to identify spatial variation for glaciers of each type. These are based on the same samples of glaciers measured from 1964-1999/2001 and 1999/2001-2009 that were used for the maps of rate change by class. Maps of rate changes in the northwest are shown in Figures 5.22 and 5.23, and maps for the southwest in Figures 5.24 and 5.25.

The maps show that there is significant variation in rates of length change for glaciers with the same terminus environment, in both study areas. Furthermore, differences in terminus environment do not explain why neighbouring glaciers of the same class were observed to retreat at different rates, as demonstrated by the northwest glaciers draining ice cap ‘A’ that were highlighted in Section 5.2.4 (Figure 5.23). Such variation in rate must, therefore, be due to other factors such as glacier length, aspect or area.

In Section 5.2.4 it was observed that glaciers around Granville Fjord (location B) in the northwest had retreated particularly large relative distances between 1999 and 2009. Figure 5.23 reveals that these glaciers and ice cap margins are all land-terminating, as are the majority of glaciers that have retreated by more than 0.51% a^{-1} during this time period. In the southwest, the southern area of ice sheet margin and outlet glaciers around Kangiata nunata sermia (location C) retreated between 1964 and 2001, whereas the rest of the ice sheet margins and outlet glaciers advanced. Figure 5.24 reveals that the retreating glaciers are a mixture of tidewater and land and lake-terminating. In addition, it is interesting to note that the independent glaciers that advanced between 1964 and 2001 were a mixture of land-terminating and tidewater, but that only tidewater glaciers advanced from 2001-2009.

The period from 1964 to 1999 spans 35 years, during which time some significant fluctuations in glacier position occurred. The most dramatic variations in length were exhibited by glaciers 48 (Farquhar Gletscher) and 49 (Tracy Gletscher; location ‘D’, Figure 5.22), which advanced and retreated hundreds of metres during this period. Overall, however, these fluctuations amounted to relatively slow retreat for Farquhar Gletscher and no net change at all for Tracy Gletscher. These results highlight the importance of putting short-term fluctuations into context with long-term trends. For example, if Tracy Gletscher had only been mapped between 1999 and 2009, the results would have suggested that prolonged and rapid retreat is occurring. In contrast, if the glacier had only been mapped between 1987 and 1999, the results would indicate that the glacier was advancing. However, by mapping this glacier at many time steps over the whole period from 1964 to 1999, it can be seen that whilst the glacier terminus fluctuated widely, it returned to its original position. Whilst Tracy Gletscher subsequently underwent extremely rapid retreat between 1999 and 2002, this slowed to a much lower rate between 2002 and 2007. Such fluctuations are not unexpected, as tidewater glaciers are known to undergo regular cycles of advance and retreat (Warren, 1991; Csatho *et al*., 2009).

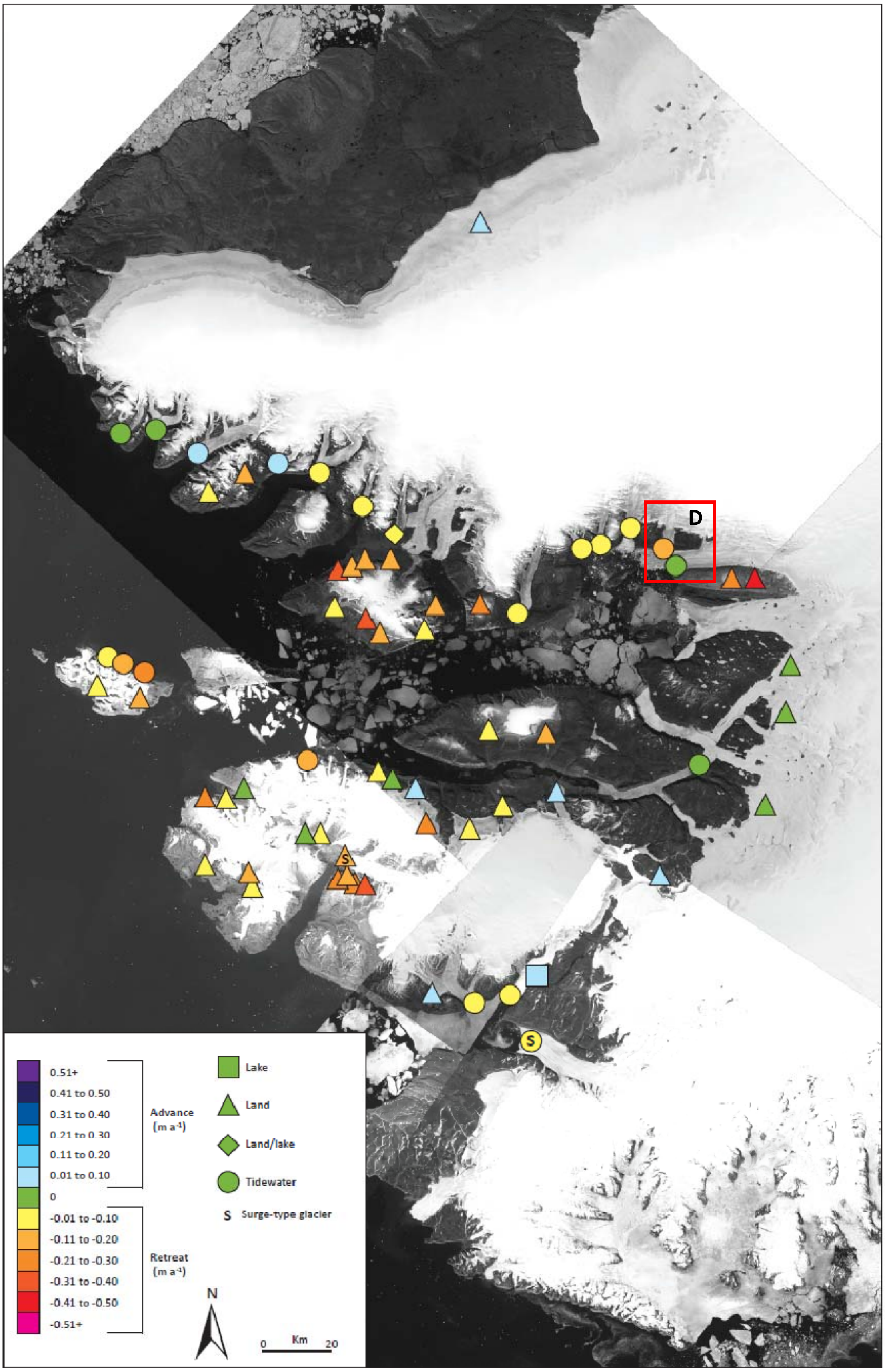


Figure 5.22: Relative length change data for all glaciers measured between 1964 and 1999 in the northwest study area. The different symbols refer to the different glacier terminus environments, and the colours to the rate of retreat or advance. Background is the 1999 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

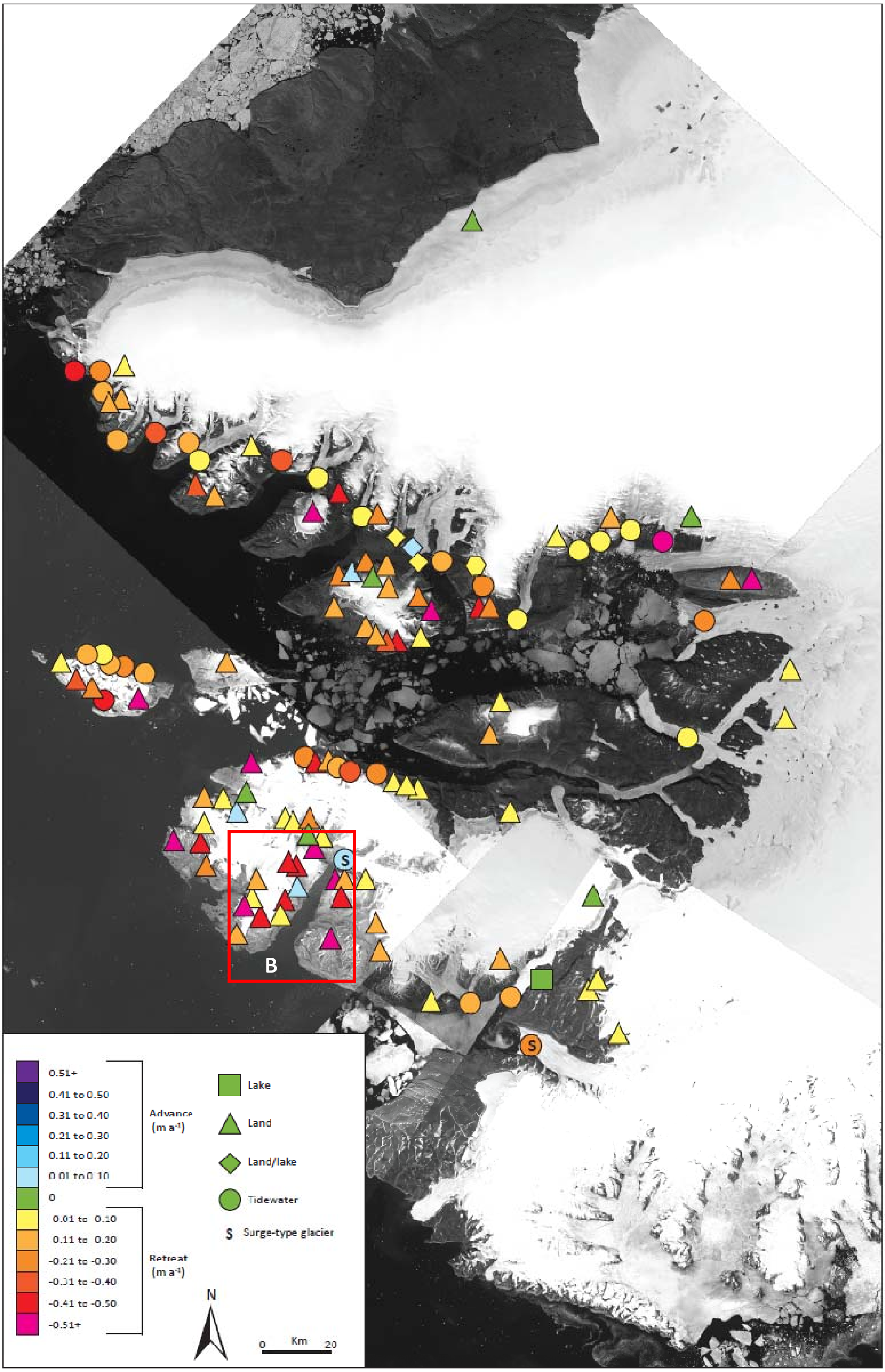


Figure 5.23: Relative length change data for all glaciers measured between 1999 and 2009 in the northwest study area. Background is the 1999 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

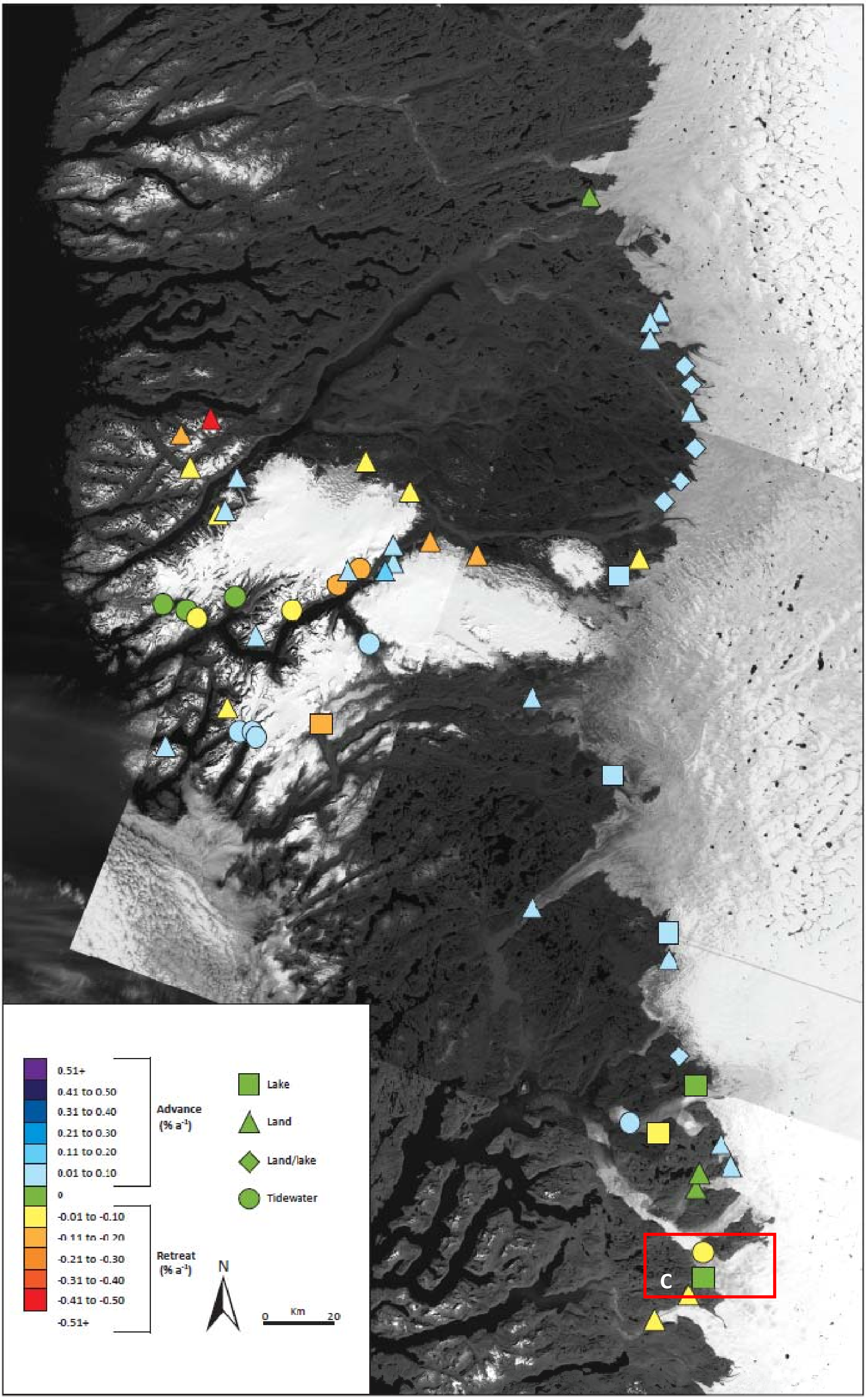


Figure 5.24: Relative length change data for all glaciers measured between 1964 and 2001 in the southwest study area. See text for discussion of location C. Background is the 1999 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

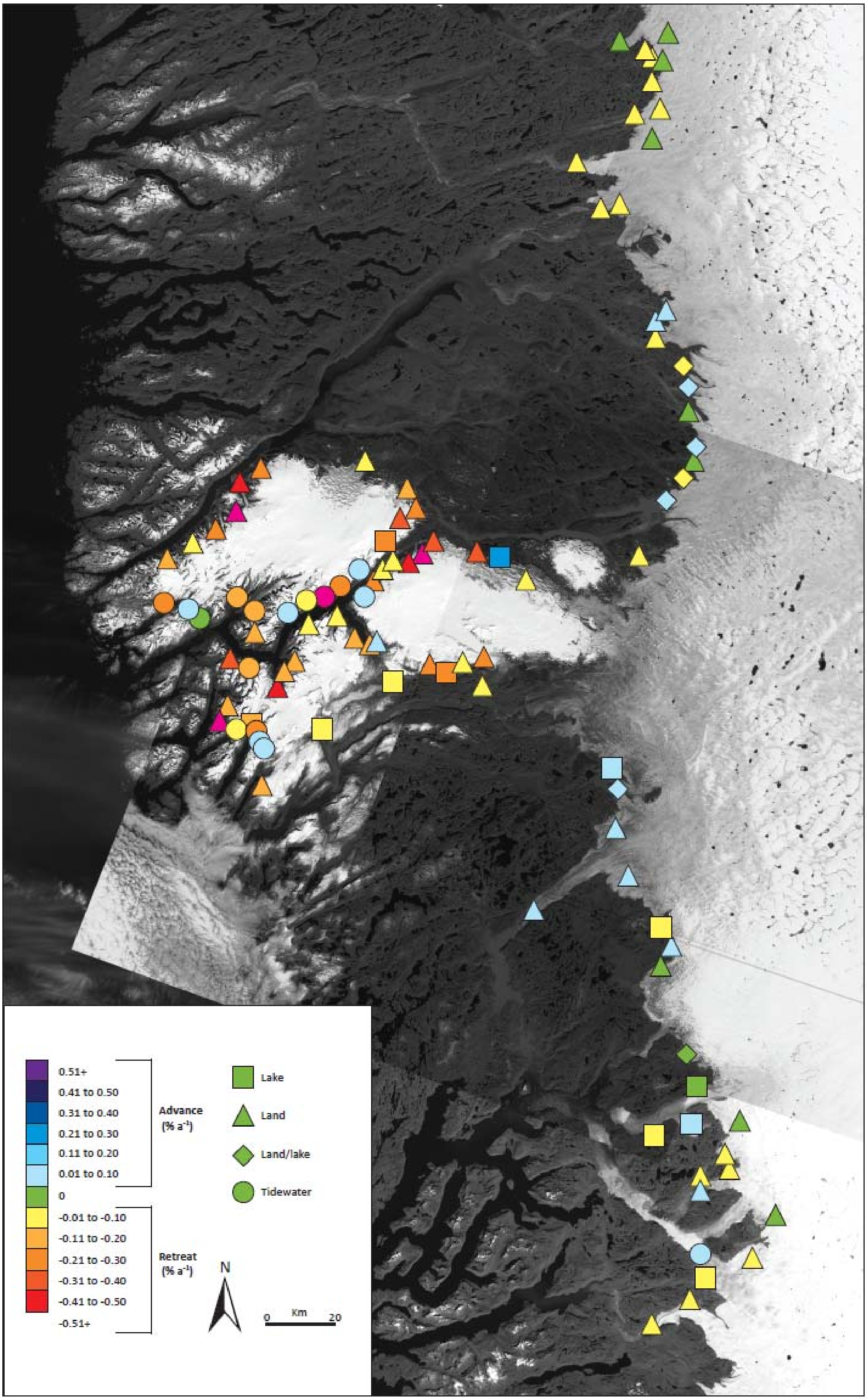


Figure 5.25: Relative length change data for all glaciers measured between 2001 and 2009 in the southwest study area. Background is the 1999 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

5.4.5 Testing the relationship between terminus environment and length changes

The relationship between terminus environment and glacier length changes will be statistically tested using one-way ANOVA and the un-transformed data for glaciers measured at 1964 and 1999/2001 (see Chapter 3, Section 3.5.5 for more details). The one-way ANOVA test gave values of p=0.02 in the northwest, and p=0.8582 in the southwest, indicating that terminus environment is only a significant influence on glacier length change in the northwest. This result is not entirely unexpected if compared to the plot of mean rate of change by terminus shown in Chapter 4 (section 4.4.4, Figure 4.24), which shows that mean rates of change between 1964 and 2001 are very similar for all termini in the southwest.

The southwest data for 2001-2009, however, have very different mean rates of change for the different terminus environments, so a one-way ANOVA test was used to see if these data are significantly different. This gave a p-value of 0.2251, which is much lower than that for 1964-2001 but still outside the 95 % confidence interval. Therefore, it would appear that terminus environment does not significantly affect behaviour in the southwest. However, it is possible that the ANOVA results have been skewed by the data distribution (which is not perfectly Normal) or the variations in class size. These results also highlight one of the difficulties inherent in statistical testing of glacier characteristics and length change, which is that the results are based on only one sub-sample of the dataset or a specific time period. If a different sample or time period were tested it may give a different result, as is the case here. In this instance, based on an assessment of the three statistical tests undertaken here and the graphs presented in Chapter 4 (section 4.4), it is concluded that terminus environment is a significant influence on glacier length changes in the northwest, and may play some role in modifying behaviour in the southwest.

5.4.6 Summary

Based on the data presented in Section 5.3, some broad observations on variations in mean rate and range by terminus environment can be made. In the northwest, both tidewater and land-terminating glaciers have retreated overall during most time periods, but tidewater mean rates of retreat appear to vary more than those of land-terminating glaciers at the decadal and two-decade time scales. Glaciers with different terminus environments also exhibit different behaviour in the southwest, with land-terminating glaciers advancing from 1964-1973, land/lake-terminating glaciers advancing from 1964-2001 and lake-terminating and tidewater glaciers retreating at all time periods. However, the increase in mean distance retreated per year for tidewater glaciers is smaller than that shown by land glaciers, which experienced the greatest change in mean rate of length change. The range of individual values for land, lake and tidewater termini are all very similar, but land/lake glaciers show much less variation.

In general, most glaciers in the southwest retreated shorter distances per year than glaciers in the northwest at most time periods, and the ranges of individual values were often smaller. Spatial maps reveal significant within-sample in both regions, which cannot be explained by glaciers belonging to different classes. In addition, the significant short-term fluctuations of some tidewater glaciers equal only small net changes in glacier length over several decades. This highlights the need to investigate changes of these glaciers over long time periods to put short-term changes into context. Finally, the spatial maps indicated that many of the glaciers that retreated the furthest relative distances overall are land-terminating. In conclusion, these data suggest that terminus environment has been a significant influence on glacier behaviour.

5.5 Additional glacier characteristics and their influence on length changes

Previous studies have shown that the timing and magnitude of glacier length change are partly controlled by independent glacier characteristics, such as length and aspect (Oerlemans, 2005; Yde and Knudsen, 2007; Citterio *et al*., 2009). In the previous two sections, spatial maps of rates of glacier length change revealed that neighbouring glaciers of the same class have often retreated significant different relative and absolute distances, despite having the same terminus environment. The aim of this section is to examine the possible links between other glacier characteristics and length change. These are length (5.4.2), aspect (5.4.3), area (5.4.4), surface slope (5.4.5) and terminus elevation (5.4.6). The results are summarised in Section 5.4.7.

5.5.1 Summary of the dataset

All analyses in the following sections are performed on one sub-sample of the glacier length change dataset. Ideally, this sample would consist of data for all 322 glaciers in the study measured over the whole time period from the LIA to 2009. However, because not all glaciers were measured at these two time steps, a balance between the longest time period and largest sample size had to be achieved. Therefore, analysis is based on a sample of 67 northwest and 58 southwest glaciers that were measured at 1964 and 1999/2001, and some summary details of these data samples are given in Table 5.12. It should be noted that this sample comprises outlet glaciers of all different classes and terminus environments, and ideally separate analysis would be carried out on each type. However, if the data set were divided up in this manner many of the resulting samples would be too small to analyse using statistical tests. For this reason, the majority of the following analyses are undertaken on the whole data set unless otherwise stated.

Data on aspect, area, slope and terminus elevation in the southwest study area are taken from the inventory published by Weidick *et al.* (1992). No such inventory has been made of northwest glaciers, so area, slope and terminus elevation are not studied for this region. Aspect was determined based on a visual assessment of the Landsat base images. In both the northwest and southwest, original glacier length was calculated based on the Landsat imagery and an ASTER GDEM, as described in Chapter

3 (Section 3.5.2). Scatter plots, one-way analysis of variance (ANOVA) and Pearson's correlation co-efficient tests are used to determine whether relationships between rate of length change and glacier characteristics are significant. As in the previous two sections, these tests were performed on un-transformed data (see Chapter 3, Section 3.5.5).

	Northwest	**Southwest**
	1964-1999	1964-2001
Number of glaciers	67	58
Mean original length (km)	23.2	39.8
Number of glaciers as proportion of total dataset (%)	43	36

Table 5.12: Summary statistics of the glacier samples analysed throughout this section.

5.5.2 Original length

Previous studies have found that longer glaciers often retreat further than shorter glaciers in absolute terms (Stokes *et al.,* 2006; Jiskoot *et al.,* 2009). This theory is tested for the northwest and southwest study areas by plotting absolute length change per year from 1964-2009 against original glacier length (Figure 5.26). Neither plot reveals a particularly conclusive trend, although the data for the southwest does give some indication that the termini of larger glaciers may have moved greater distances than those of smaller glaciers. A Pearson's correlation co-efficient test gave r-values of 0.07 for the northwest and 0.30 for the southwest study area. This indicates that there is no significant correlation between original length and absolute rate of change in the northwest, and only a weak correlation in the southwest. The absence of a clear trend may be the result of confounding factors, such as terminus environment.

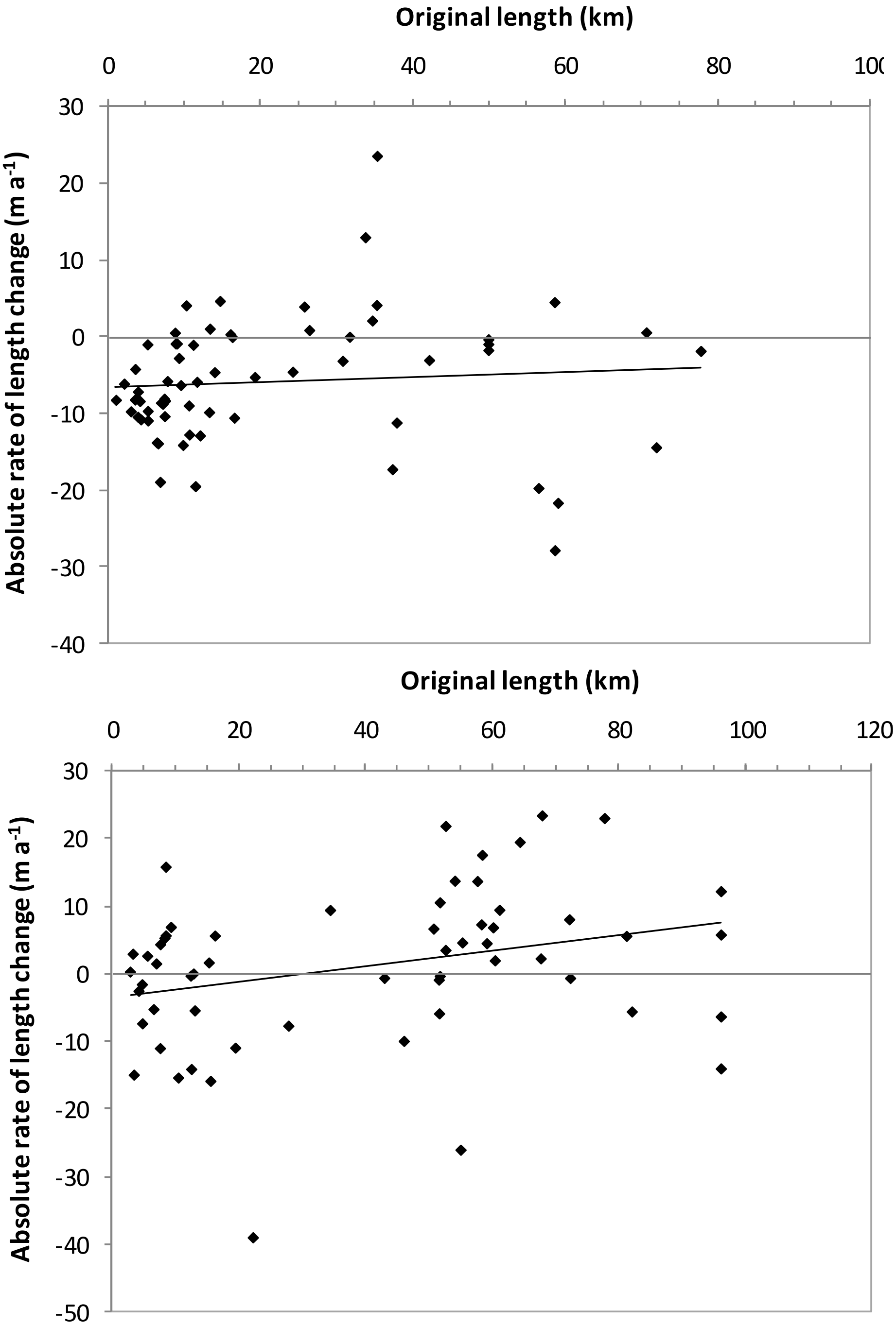
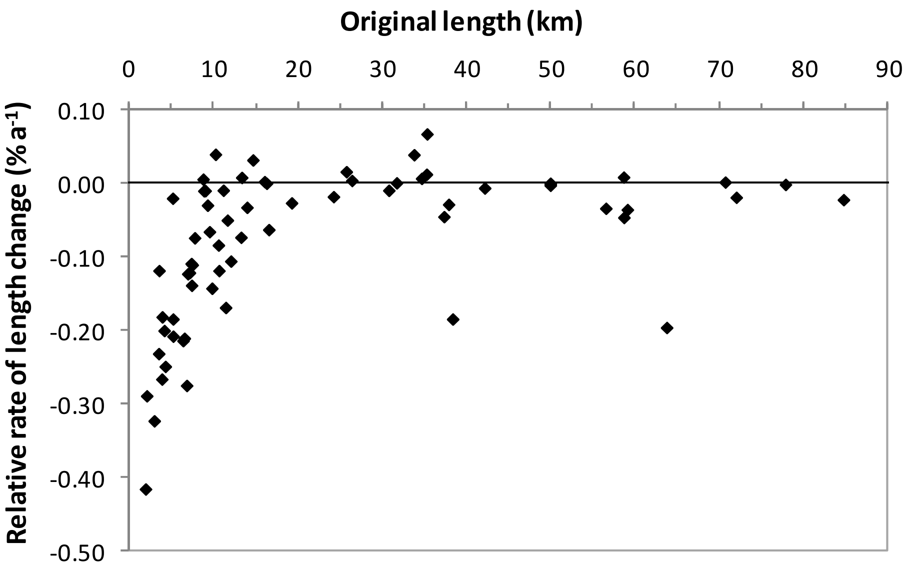


Figure 5.26: Scatter plots of overall original length plotted against absolute length change for all glaciers measured between 1964 and 1999/2001 in a) the northwest and b) the southwest.

Original lengths are also plotted against the relative retreat data in Figure 5.27. These data suggest that the shortest glaciers in both study areas have advanced or retreated further than the longest glaciers, as a percentage of their overall length. This result is not unexpected, given that length change analysis for the different glacier classes suggested that the long ice sheet outlet glaciers generally retreated shorter distances as a percentage of length than did the shorter independent ice cap and mountain glaciers (see Section 5.2). These relationships are tested using Pearson's correlation co-efficient, which gave r-values of 0.46 for the northwest, and 0.23 for the southwest. These results indicate that there is some correlation between original length and relative glacier retreat, particularly in the northwest. The weakness of this relationship probably reflects the influence that confounding factors such as terminus environment and aspect have upon the results.



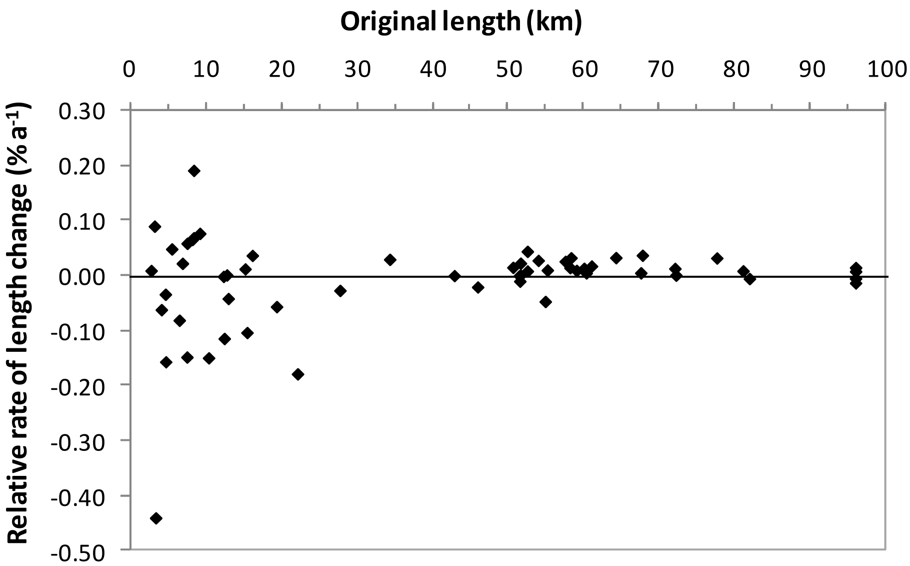


Figure 5.27: Scatter plots of overall original length plotted against relative length change for all glaciers measured between 1964 and 1999/2001 in a) the northwest and b) the southwest.

5.5.3 Aspect

Firstly, the mean rates of length change for glaciers with each aspect (N, NE, E, SE, S, SW, W and NW) are plotted onto graphs for each study area (Tables 5.13 and 5.14, and Figures 5.28 and 5.29). The results suggest that glaciers with a northeast aspect in the northwest, and north and south aspects in the southwest, may have retreated the furthest distances between 1964 and 2009. One-way ANOVA tests were used to determine whether there is any statistical difference between the mean rates, and these gave p-values of 0.08 and 0.04, respectively. This suggests that aspect has only significantly influenced glacier behaviour in the southwest. However, the class sizes tested here are very uneven as only a few glaciers with some aspects were mapped.

To increase the size of the samples being tested, a broader comparison of north and south glaciers (NW-E vs. W-SE) and east and west glaciers (N-SE vs. S-NW) was made for the northwest study area. The mean rates of retreat for each class indicated that north and east facing glaciers retreated greater distances as a proportion of their overall length than did south and west facing glaciers. One-way ANOVA tests gave p-values of 0.01 and 0.12 respectively for each comparison, indicating that only the north and south facing glaciers have significantly different rates of retreat. Similar analysis of glaciers with opposite aspects in the southwest indicated that north and east facing glaciers have retreated significantly greater distances than south and west facing glaciers.

These results are probably a reflection of the differences in mean rate between glaciers of different classes, however. The south and west facing samples include many ice sheet outlet glaciers, whereas the north and east samples include only independent ice cap outlets and mountain glaciers. The data presented for these different classes in Section 5.3 showed that the ice sheet outlet glaciers have generally retreated much smaller distances as a proportion of their overall length than have the independent glaciers.

Orientation	Mean relative rate of length change (% a^{-1})	Number of glaciers
N	-0.09	14
NE	-0.21	2
E	-0.08	3
SE	-0.07	5
S	-0.05	12
SW	-0.05	12
W	-0.03	9
NW	-0.12	8

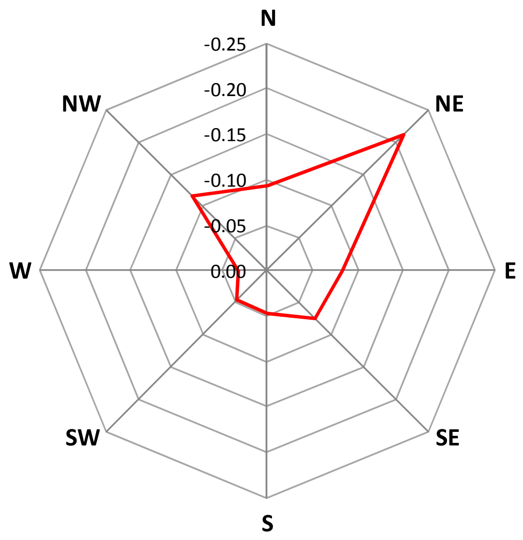


Table 5.13: Mean relative rate of length change and number of northwest glaciers measured for each aspect between 1999 and 2001.

Figure 5.28: Diagram showing mean relative rate of length change for northwest glaciers with different aspects measured between 1999 and 2001.

Orientation	Mean relative rate of length change (% a^{-1})	Number of glaciers
N	-0.07	7
NE		0
E		0
SE	-0.03	4
S	-0.07	3
SW	0.00	13
W	0.02	19
NW	-0.03	11

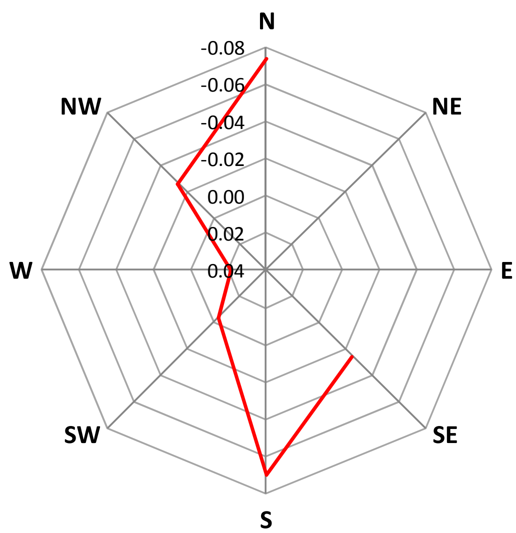
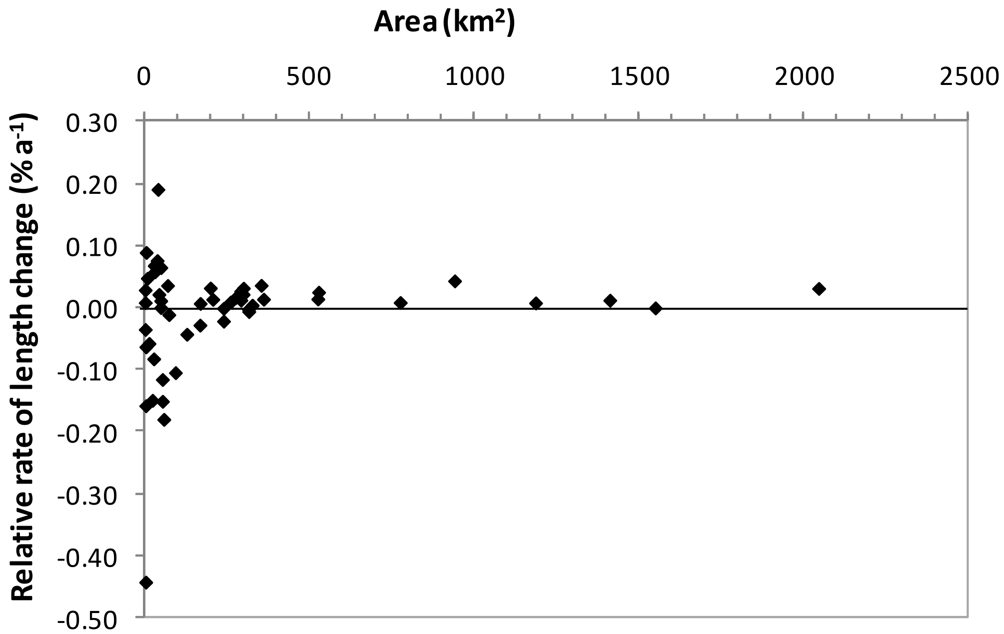


Table 5.14: Mean relative rate of length change and number of southwest glaciers measured for each aspect between 1964 and 2001.

Figure 5.29: Diagram showing mean relative rate of length change for southwest glaciers with different aspects measured between 1964 and 2001.

5.5.4 Area

The glaciers mapped in the southwest between 1964 and 2001 range in area from 2.1 to 2048 km^2, and are arbitrarily grouped into three classes: small (0-20 km^2), medium (21-200 km^2) and large (201-2050 km^2). These classes have mean rates length change of -0.066 % a^{-1}, -0.16 % a^{-1} and 0.013 % a^{-1} respectively. The one-way ANOVA test gives a p-value of 0.089, however, so area does not appear to have a significant impact on glacier length change. To test this conclusion, all glacier areas were plotted against relative and absolute length changes (Figure 5.30). The graphs suggest that smaller glaciers may have retreated slightly further than larger ones, but it is not a clear trend. A Pearson's correlation co-efficient test gives r-values of 0.18 and 0.39 for relative and absolute length changes, respectively. This suggests a weak relationship of glaciers with larger areas having retreated further than smaller glaciers.



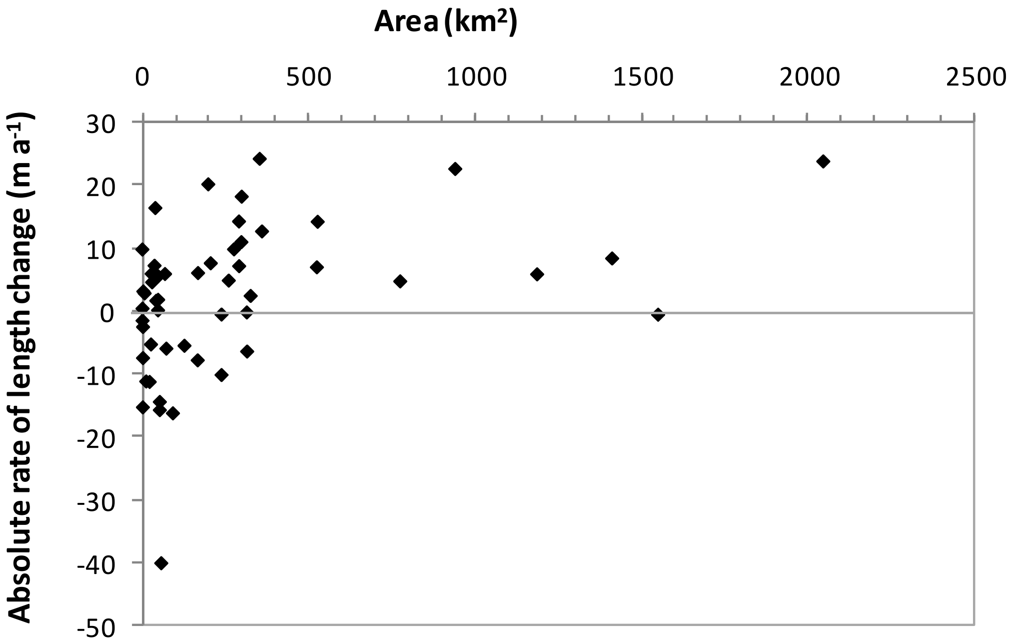


Figure 5.30: Scatter plot of area plotted against absolute and relative rate of length change for all glaciers measured between 1964 and 2001 in the southwest. Area data are from Weidick *et al*. (1992).

5.5.5 Slope

Glacier slope was calculated for southwest glaciers by first determining the difference between maximum and terminus elevation (based on data from Weidick *et al.*, 1992). This was then divided by original length. The results are plotted against absolute and relative length change in Figure 5.31. There is no obvious relationship, and this is confirmed by Pearson's correlation co-efficient tests, which gave r-values of 0.09 for relative rates and -0.19 for absolute rates. A comparison of rate changes and slope for just independent glaciers also showed no relationship.

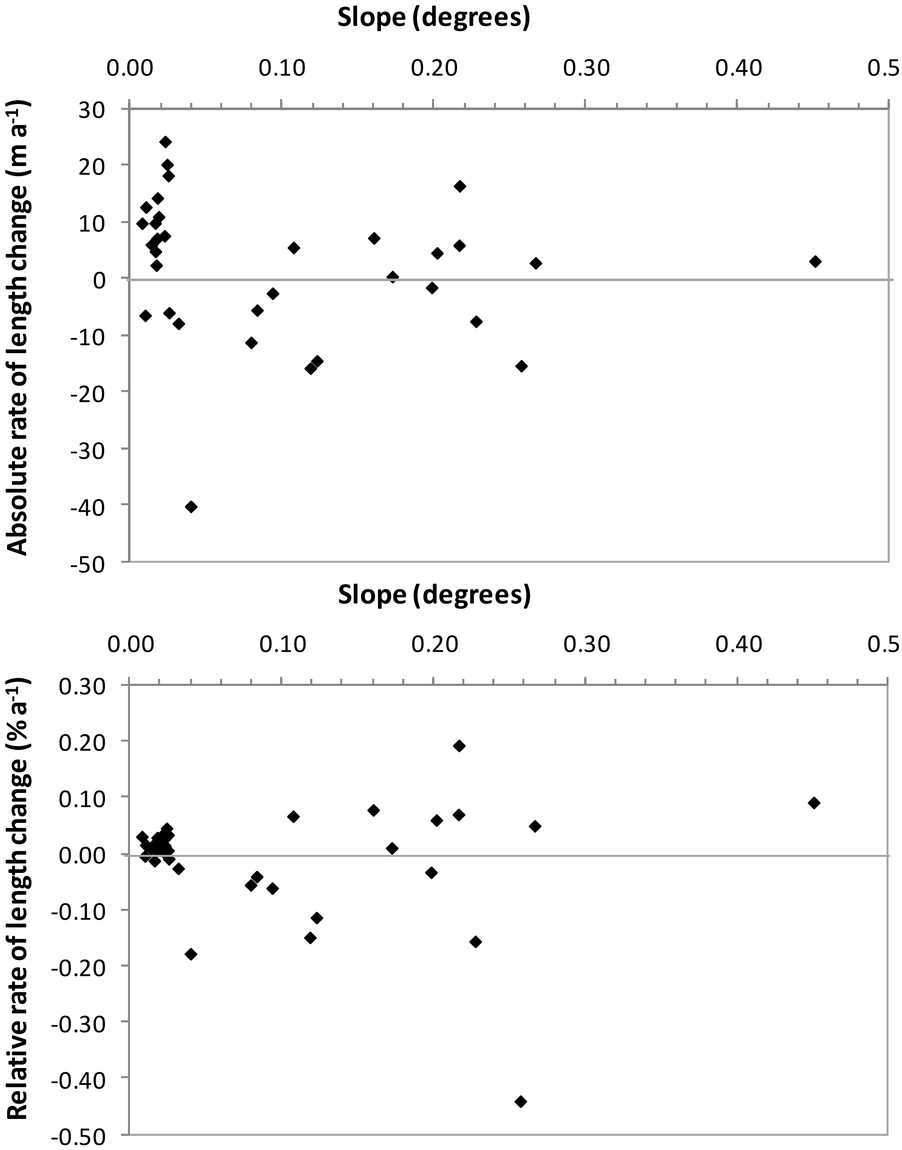


Figure 5.31: Scatter plots of glacier slope plotted against absolute and relative rate of length change for all glaciers measured between 1964 and 2001 in the southwest. Slope was calculated as elevation change divided by original length. Elevation data are from Weidick *et al*. (1992).

5.5.6 Terminus elevation

Scatter plots of terminus elevation against absolute and relative rates of length change are shown in Figure 5.32. The data show no signs of correlation, and this is confirmed by Pearson's correlation co-efficient, which gave r-values of 0.00 and -0.08 respectively. This sample includes glaciers of all terminus environments and classes. If measurements for more glaciers were available it would be interesting to examine glaciers in separate groups. However, scatter plots of terminus elevation against length change of independent glaciers also showed no signs of correlation.

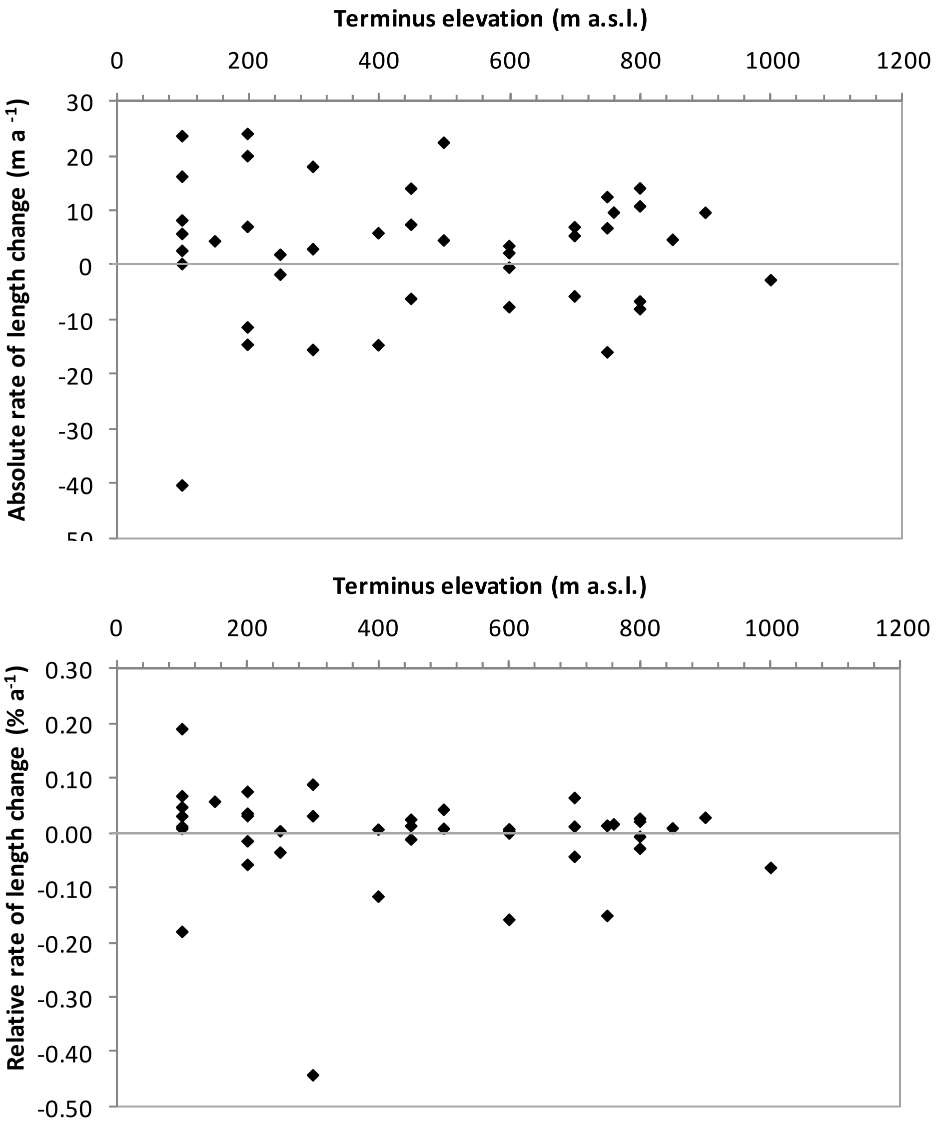


Figure 5.32: Scatter plots of glacier terminus plotted against absolute and relative rate of length change for all glaciers measured between 1964 and 2001 in the southwest. Elevation data are from Weidick *et al*. (1992).

5.5.7 Summary

In this section, the one-way ANOVA test, Bonferroni test, Pearson's correlation coefficient and scatter plots have been used to statistically examine the relationship between glacier characteristics and the relative speed of length changes. The results suggest that length, aspect and area may have some influence on rates of retreat. No link was found between slope, terminus environment and length change. However, all analysis in this section will have been affected by confounding variables, in particular class and terminus environment, so the results are inconclusive.

5.6 Summary of the chapter

In this chapter, possible drivers and controls of glacier length changes have been investigated. The links between climate and length change were first explored, and data from regional meteorological stations showed that both temperatures and precipitation levels are higher in the southwest than the northwest. Glaciers in the southwest appear to have responded to climate changes within a decade, although it is not clear how lag times vary for different classes and terminus environments. In both the northwest and southwest the rapid increase in air temperature since the 1990s has been matched by an increase in mean glacier retreat per year.

Examination of glacier retreat rates by class revealed it to be a dominant control on length change, with independent glaciers retreating significantly further in relative terms than the ice sheet outlet glaciers and margins. Indeed, the ice sheet margins do not appear to have advanced or retreated at all overall in either study at any time period. In the southwest, the ice sheet margins and outlet glaciers advanced from 1964 and 2001, whereas ice cap outlet glaciers only advanced during the 1960s. Terminus environment was also found to have a significant influence on length changes, particularly in the northwest. Rates of tidewater glacier retreat fluctuated at decadal and two-decade time scales, but most underwent very little net change in length overall. In the southwest, lake-terminating glaciers have retreated at similar rates to land-terminating and tidewater glaciers, but land/lake-terminating have undergone very little change in length at any time period.

A number of other factors have been investigated, and some link between length, aspect, area and length change was found, although the results were not conclusive. The results of the statistical tests should be treated with caution, however, as the results can be influenced by more than one variable. For example, in the southwest study area all outlet glaciers have an approximately western aspect, so the test of east *vs.* west rate changes is also a test of ice cap outlets and mountain glaciers against a sample of mostly ice sheet outlet glaciers. The results could, therefore, simply be confirming that class has a significant influence on length changes. Similarly, virtually all of the glaciers classified as 'long' are ice sheet outlet glaciers, whilst the majority of 'short' glaciers are ice cap, icefield and mountain outlets. This could indicate that statistical analysis of size was partly testing the significance of class, or conversely, that analysis of different classes is a proxy for the influence of size. In order to truly test the influence of each individual characteristic, such as class, other variables would ideally have to be kept the same (i.e. use glaciers of the same length, aspect, terminus environment). Alternatively, these variables would need to be randomly distributed, with each class containing the same proportion of short and long/east and west glaciers. It is impossible to control all variables in a real world environment, however, so the best approach is simply to test as many glaciers as possible.

Chapter 6

Discussion

6.1 Introduction

This chapter draws together the results presented in Chapters 4 and 5 to address the main aims and research questions of the project, and discuss the key findings in the context of previously published research. The primary aim of this research was to examine and compare the fluctuations of the ice sheet margin, ice sheet outlet glaciers, independent ice caps and mountain/valley glaciers in two regions of West Greenland during the twentieth century, with relation to climatic and non-climatic controls. This overall aim was broken down into more specific research objectives, which were: to compare patterns of glacier length change in the north and south; to examine differences in length change for different glacier classes; to investigate the influence of terminus environment on length change; and to assess links between length change and regional climate data (see Chapter 1 for more details). These objectives are addressed in the following sections. The main drivers and controls of glacier length changes are discussed first in Section 6.2. The fluctuations of northwest and southwest glaciers are compared to published data on twentieth century glacier behaviour in these regions in Sections 6.3 and 6.4, respectively, and differences between the two regions examined in Section 6.5. Finally, the major limitations of the study are discussed in Section 6.6.

6.2 Controls on glacier fluctuations

6.2.1 Are glacier length changes controlled by climate?

A number of factors complicate assessment of the links between climate and terminus change. Firstly, the meteorological data often contain unknown errors, particularly prior to the 1950s (Box, 2002). Secondly, decadal measurements of terminus position are only available for a small number of glaciers in this study. Thirdly, whilst terminus changes can occur rapidly if conditions lead to increased ablation, there is a much greater lag time between increased accumulation and ice front response (Nye, 1960; Gordon, 1981). Fourthly, glacier response to climate change is known to be moderated by individual glacier characteristics such as size and terminus (Gordon, 1981; Warren, 1991). Finally, sea surface temperatures are likely to play a significant role in triggering tidewater glacier retreat (Rignot *et al.,* 2001), but only air temperatures and precipitation were considered in this study.

In Chapter 5, air temperature and precipitation data from eight meteorological stations in the northwest and southwest study areas were presented alongside glacier length change fluctuations. Without any data on mass balance it was not possible to statistically test for a relationship between climate and rate of length changes, so analysis was based solely on visual comparisons. Recent acceleration in terminus retreat in both study areas from 1999 onwards may be due to the rapid increase in air temperatures since the 1990s. In addition, the significant retreat of southwest glaciers during the 1940s and 1950s could be explained by the apparently high temperatures and low precipitation recorded during the 1930s and 1940s.

Previous authors have variously concluded that precipitation is the main driver of glacier change (Davies and Krinsley, 1962; Gordon, 1981), or that air temperature is the dominant control on fluctuations (Weidick, 1968; Warren, 1991; Yde and Knudsen, 2007). It is expected that higher air temperatures or a decrease in precipitation should lead to increased retreat (Davies and Krinsley, 1962; Oerlemans, 2005). In this study, air temperature appears to have been the dominant control on glacier fluctuations in the southwest during the past two decades, as the mean distance retreated per year increased from 2001-2009 following a period of rising air temperatures, but also increased precipitation. However, this trend may also be explained by the greater lag time between increased accumulation and terminus response (Nye, 1960). It is likely that both variables affect glacier fluctuations to some degree, and the data presented here are insufficient to convincingly decide which is the dominant factor.

Research suggests that glacier terminus position changes lag climate changes by < 30 years, although the exact time depends on glacier size (Weidick, 1968; Gordon, 1981). The southwest decadal measurements of length change appear to have lagged temperature by less than 10 years, and precipitation by 10-15 years, but with such a small sample size the results are not conclusive. In addition, the actual lag will almost certainly vary between classes, and sections of the ice sheet margins may still be responding to climate changes of the last glacial-interglacial transition (Huybrechts, 1994). In summary, it is highly probable that glacier length changes are triggered by climate change, but this cannot be demonstrated convincingly from the data presented in this study.

6.2.2 To what extent does class influence glacier length change fluctuations?

Research suggests that the response of Greenland glaciers to climate change is strongly controlled by their class (e.g. ice sheet or ice cap; Gordon, 1981). One of the objectives of this study was to test whether glaciers of different classes in the northwest and southwest regions have undergone significantly different changes in length. A visual comparison of graphs and spatial maps of relative length change data indicated that glaciers in different classes had retreated or advanced at varying speeds (Chapter 5, Section 5.3). Ice sheet margins underwent no significant retreat or advance at any time period in either study area, whilst ice sheet outlet glaciers retreated and advanced relatively short distances as a proportion of their overall length compared to other classes. In general, independent glaciers retreated the greatest distances relative to their overall length. A different pattern is seen when examining absolute length changes, with ice sheet outlet glaciers retreating greater distances than ice cap margins or ice cap, icefield and mountain glaciers. Ice sheet margins, however, were again seen to undergo no significant advance or retreat.

Previously, Gordon (1981) has suggested that small mountain glaciers lag climate changes by up to 9 years, and that larger ice cap and icefield outlet glaciers lag climate by 20 to 30 years, whilst Weidick (1968) suggested that the main ice sheet outlet glaciers and margins take between 2 and 20 years to respond to climate changes. The evidence presented in Chapter 4 (Section 4.2.3) for decadal fluctuations of different glaciers suggests that ice cap outlet glaciers are more sensitive to climate changes than the ice sheet outlet glaciers in the southwest. Between 1964 and 2009 ice sheet outlet glaciers underwent very little advance or retreat relative to their overall length, unlike the ice cap outlet glaciers. A similar trend applies when examining the absolute length change data, which indicates that ice cap outlet glaciers retreated further from

2001-2009 following the increase in air temperatures, compared to ice sheet outlet glaciers which retreated only a very short distance overall. The data appear to support the hypothesis that the smaller independent ice cap outlet glaciers respond more quickly to climate changes, and have retreated greater distances as a proportion of their overall length, than the large ice sheet outlet glaciers. However, more glacier measurements are required to test this conclusion.

One of the most interesting features to emerge from the class analysis is the prolonged period of mean advance of the ice sheet margins and outlet glaciers in southwest Greenland between 1964 and 2001. Previous studies have identified the beginning of this advance, but the data presented here are the first to demonstrate that terminus positions have continued to advance since the 1980s (Weidick, 1968; 1991; 1995). Surveys of the surface elevation of the Greenland ice sheet during the 1970s indicated that the southwest region was thickening (Zwally *et al.,* 1989), and this is supported by modelling of long-term surface elevations, which indicates that this region has thickened significantly overall since the Little Ice Age (Huybrechts, 1994). It has been suggested that the ice sheet in this region retreated particularly strongly during the last glacial-interglacial transition, and the current advance is the result of the long- term readjustment of the margins, which is sufficient to outweigh the ablation resulting from short-term temperature increases (Huybrechts, 1994).

Alternatively, Zwally *et al.* (2002) suggested that the advance of the ice sheet in the southwest may be partly due to increased surface melting after air temperatures increased, which increases ablation at the margin causing it and the outlet glaciers to retreat. This in turn leads to an increase in ice thickness and surface slope, which cause basal shear stress to increase. Higher basal shear stresses coupled with more meltwater reaching the bed is likely to result in faster flow of the ice sheet. The resulting flux of ice from the accumulation to the ablation zone will result in slower retreat and a decrease in ice sheet thickness, which in a warming climate will allow the ablation area to increase. This results in a larger area of ice sheet undergoing meltwater-induced sliding, until eventually the ice sheet margin switches from slow advance, no net length change or slow retreat to rapid retreat (Zwally *et al.,* 2002; Parizek and Alley, 2004). It is possible that increased ablation following the warm temperatures in southwest Greenland between 1920 and 1960 led to meltwater-induced sliding and advance of the ice sheet during the following decades. If this hypothesis is correct, the model suggests that the ice sheet margin is likely to retreat rapidly in the future, if temperatures continue to rise. The ice sheet margin has a relatively shallow surface slope in West Greenland, which will aid the rapid expansion of the ablation zone.

6.2.3 To what extent does terminus environment influence glacier fluctuations?

Previous research suggests that the timing and magnitude of glacier length change fluctuations are partly controlled by the terminus environment (e.g. Weidick, 1959; Warren, 1991; Howat *et al.,* 2008). The graphs and spatial maps presented in Chapter 5 (Section 5.4) showed changes in glacier lengths over different time periods, grouped by terminus environment. The results consistently indicated that land/lake-terminating glaciers underwent less relative retreat than lake, land and tidewater glaciers at all time periods in the southwest, but there was no significant difference in mean rates or patterns of retreat for these latter three types. Conversely, a significant difference in length changes between land and tidewater glaciers was found in the northwest, where tidewater glaciers fluctuated widely between large and small distances retreated at decadal and two-decade time periods, whilst land glaciers underwent only slight changes in rate of retreat. This is not unexpected, as many authors have reported that tidewater glaciers undergo significant cyclical fluctuations in rate of length change, from slow retreat to advance to rapid retreat (Weidick, 1959; Meier and Post, 1987; Warren, 1991; Csatho *et al.,* 2008).

When examining northwest tidewater glacier fluctuations over longer time periods, however, it was observed that they have generally retreated shorter relative and absolute distances overall than land glaciers. The fluctuations of Glacier 49 (Tracy Gletscher) are a particularly striking example of this behaviour, as terminus mapping revealed that it advanced and retreated by up to 1800 metres between 1964 and 2001, equating to no net change overall during this period. This behaviour is not unique within the northwest study area, and it has important implications for the recent extensive research into tidewater glaciers fluctuations of the past two decades. Many recent studies have found that tidewater outlet glaciers around the whole of the Greenland ice sheet have retreating at accelerated rates since the 1990s (e.g. Howat *et al.,* 2008; Moon and Joughin, 2008; Box, 2009; see Chapter 2, Section 2.3.3). However, the results presented in this study highlight the need for long-term analysis of tidewater glacier terminus fluctuations to assess whether this retreat is unprecedented.

Decadal fluctuations of tidewater glaciers in the southwest study area could not be assessed due to insufficient measurements, but data for 5 tidewater glaciers measured at the two-decade time scale showed no significant fluctuations in rate, although more measurements are required to confirm this trend. Tidewater glacier fluctuations are controlled by fjord topography, water depth and ocean temperatures (Warren, 1991; Meier and Post, 1987; Rignot and Kanagaratnam, 2006; Csatho *et al.,* 2008). The apparent difference in tidewater glacier behaviour in the northwest and southwest could, therefore, reflect differences in one of the above factors. Tidewater glaciers in the northwest generally terminate into large fjords and bays that are directly connected to the ocean, whereas southwest glaciers terminate in long, narrow fjords many kilometres from the ocean. It is possible that these fjords may dampen the effects of ocean temperature changes, although without data on sea surface temperatures this is impossible to assess. In addition, the southwest fjords may be shallower than large bays in the northwest, so tidewater glacier termini are more likely to remain grounded.

The few studies to have examined the fluctuations of land-terminating glaciers concluded that they have generally retreated more slowly than neighbouring tidewater glaciers in absolute terms (Howat *et al.,* 2008; Moon and Joughin, 2008). However, the graphs of long-term absolute retreat for glaciers with different terminus environments that were presented in Chapter 5 (Section 5.4.1) suggest that land-terminating glaciers in the southwest and northwest have retreated similar distances to tidewater glaciers over most long time periods, such as 1964-2001. Further research into this behaviour is required, however, as only a small number of tidewater ice sheet outlet glaciers in the southwest and land glaciers in the northwest could be measured, making comparisons within each region difficult.

Warren (1991) undertook a detailed review of the fluctuations of glaciers with different terminus environments in southwest Greenland, and concluded that those terminating in lakes are the first to respond to climate changes, followed by tidewater and finally land glaciers. It is difficult to assess the relative response times of different glacier categories in this study due to the small number measured at the decadal time scale. Nevertheless, the data for glaciers measured at four time steps between 1964 and 2009 indicates that land/lake-terminating glaciers are the least sensitive to climate changes in the southwest, as they have undergone very little change length at all time steps. No definite conclusions can be drawn about the remaining glaciers in the southwest, and the fluctuations of tidewater glaciers in the northwest make it impossible to tell whether they or land glaciers responded first to climate changes.

6.3 Glacier fluctuations in northwest Greenland

6.3.1 Comparison with previous studies of twentieth century length change fluctuations

Previous research into glacier fluctuations in northwest Greenland was outlined in Chapter 2. The most detailed study of twentieth century fluctuations was carried out by Davies and Krinsley (1962), who surveyed 117 ice sheet outlet glaciers and 35 independent ice cap, icefield and mountain glaciers in the northwest region of Greenland between the 1890s and 1960s. They reported that all but one of these glaciers were either stationary or retreating during this period, and that 68% of ice sheet outlet glaciers had retreated compared to 80% of independent glaciers (Table 6.1). In comparison, 87.5% of the 8 ice sheet outlet glaciers and 80% of the 30 independent glacier measured in this study had retreated between the LIA and 1964, and none were observed to advance (See Table 6.1). The discrepancy between the two ice sheet outlet glacier samples could be due to the small sample size in the present study. The glacier length changes reported by Davies and Krinsley (1962) are also shown on the map in Figure 6.1. For the purposes of comparison, the absolute length change data from this study for the LIA -1964 are also shown on a map in Figure 6.2 (see Chapter 4, Figure 4.3 for data as a graph). Both maps show very similar patterns of spatial retreat, with the ice sheet outlet glaciers generally retreating greater distances than the ice cap, icefield and mountain glaciers, despite different glaciers having been measured in each study.

	Ice sheet outlet glaciers			Independent glaciers		
	Advancing	Stationary	Retreating	Advancing	Stationary	Retreating
Davies and Krinsley (1962)	1 (0.8)	36 (31)	80 (68)	0	7 (20)	28 (80)
This study	0	1 (12.5)	7 (87.5)	0	6 (20)	24 (80)

Table 6.1: A comparison of glacier behaviour as reported by Davies and Krinsley (1962: 128) and the present study for the period from the LIA to 1964. The number of glaciers in each category is shown, and given as a percentage of total sample size in brackets. The data used are the total absolute retreat in metres. Following the method of Davies and Krinsley (1962), any glacier measured in this study that had retreated less than 100 metres over all was classified as stationary.

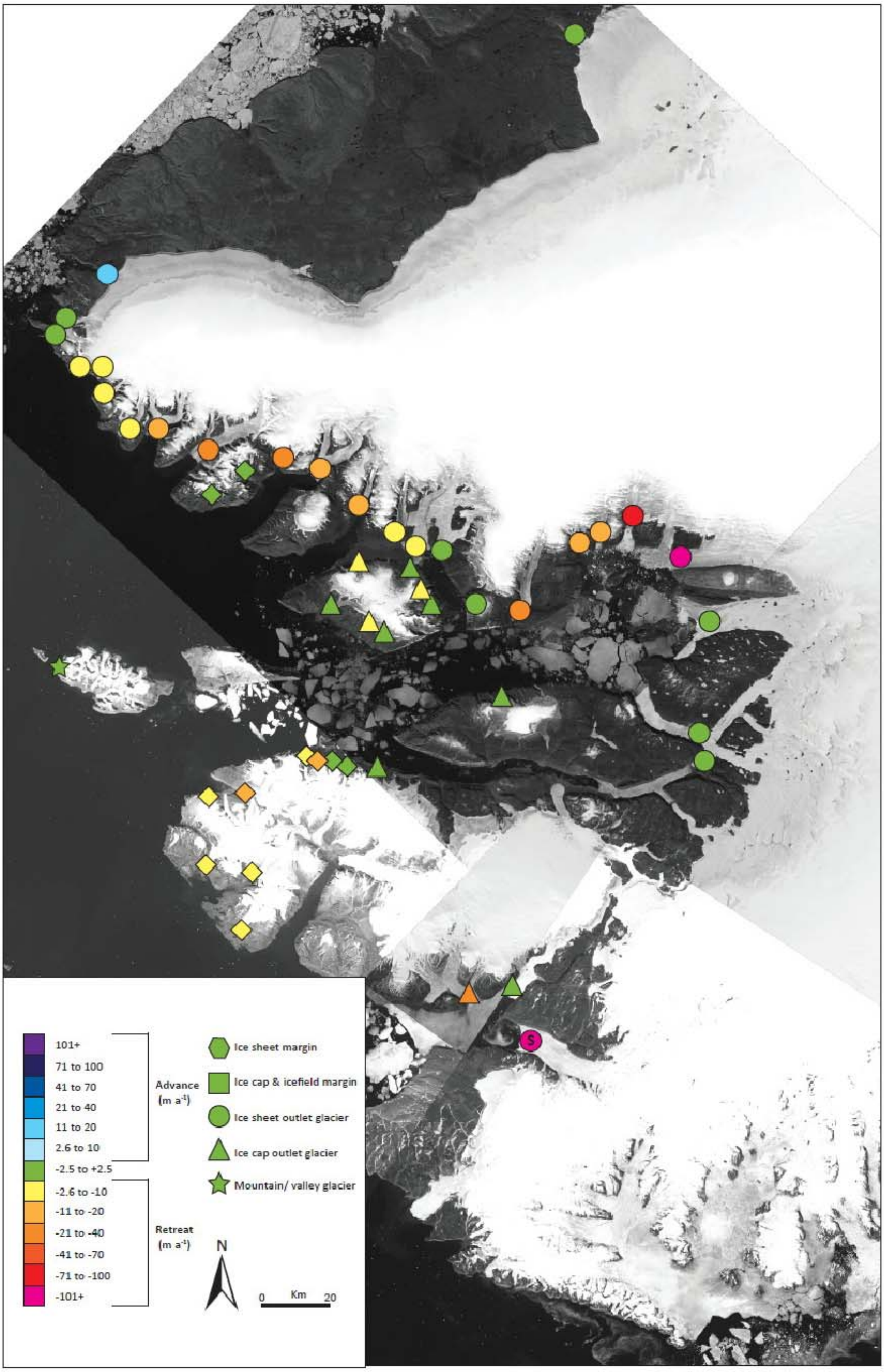


Figure 6.1: Map showing absolute glacier retreat per year between the late 1800s and 1956 in the northwest, as calculated by Davies and Krinsley (1962). Background is the 1999 Landsat TM base image displayed using bands 4,3,2 (red, green, blue).

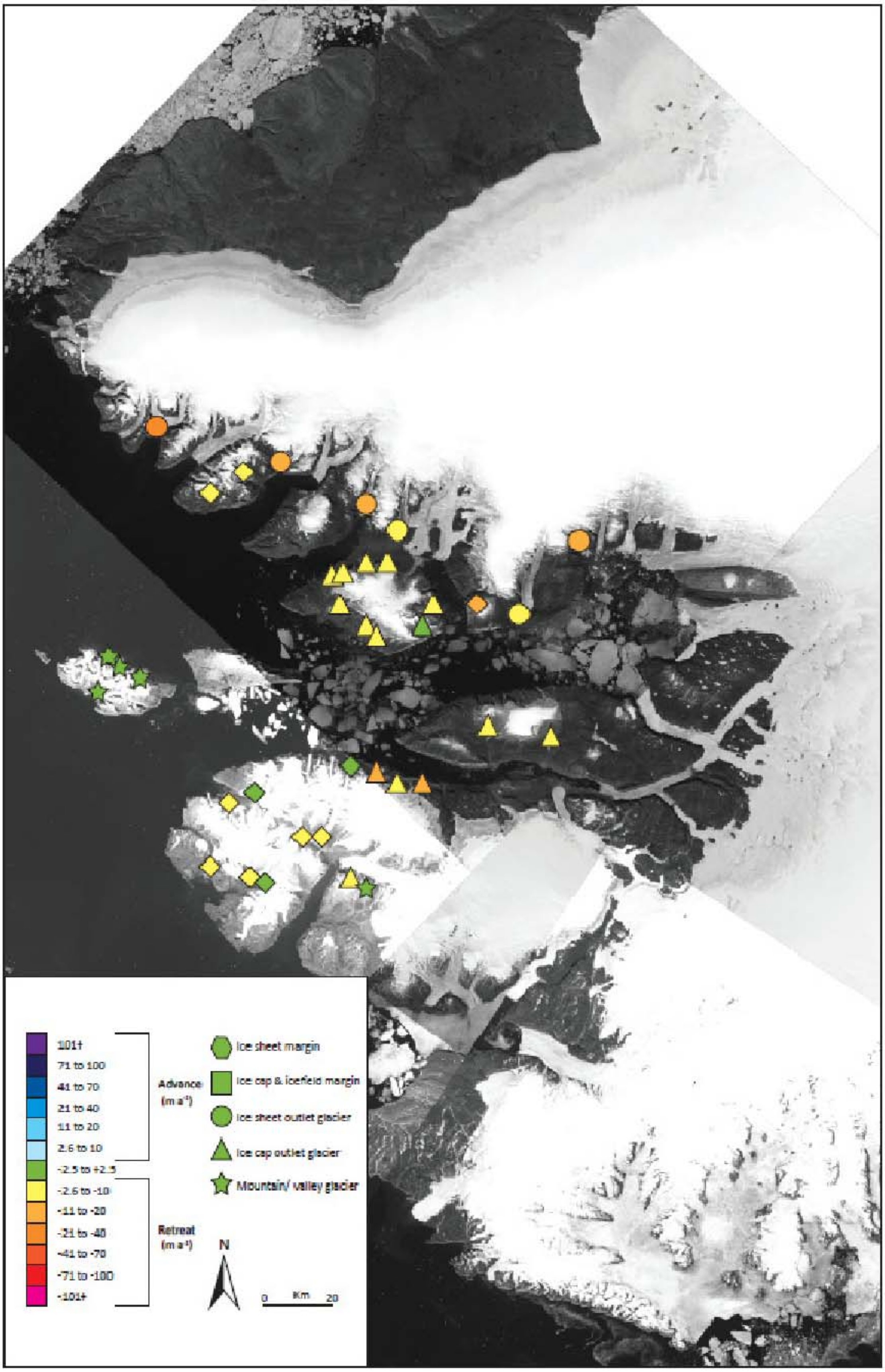


Figure 6.2: Map showing absolute glacier retreat per year between 1890 and 1964 in the northwest, based on the data previously analysed in Chapter 4 (Section 4.2). Background is the 1999 Landsat TM base image displayed using bands 4,3,2 (red, green, blue).

6.3.2 Tracy and Heilprin Gletschers

Previous studies have paid particular attention to ice sheet outlet glaciers Tracy and Heilprin (Glaciers 49 and 50 in this study), and all have reported that significant retreat occurred during the twentieth century (Davies and Krinsley, 1962; Kollmeyer, 1980; Dawes and Van As, 2010). Most recently, Dawes and Van As (2010) mapped Tracy and Heilprin Gletschers at 8 time steps between 1892 and 2009 from historical maps, aerial photographs and Landsat satellite imagery. From these results, they estimate that Tracy Gletscher retreated ~15 km over the 115 year period, which is approximately equivalent to 100 km^2 or 20 km^3 of ice loss. In this study, Tracy and Heilprin Gletschers were mapped at 7 and 8 time steps respectively between 1964 and 2009, and the cumulative length changes of glaciers 45 to 49 between 1964 and 2009 are shown in Figure 6.3. These data can be extended by mapping the approximate position of the terminus from published maps in 1892 (Peary, 1898), 1922 (Dawes and Van As, 2010) and 1947 (Kollmeyer, 1980; see Figure 6.4).

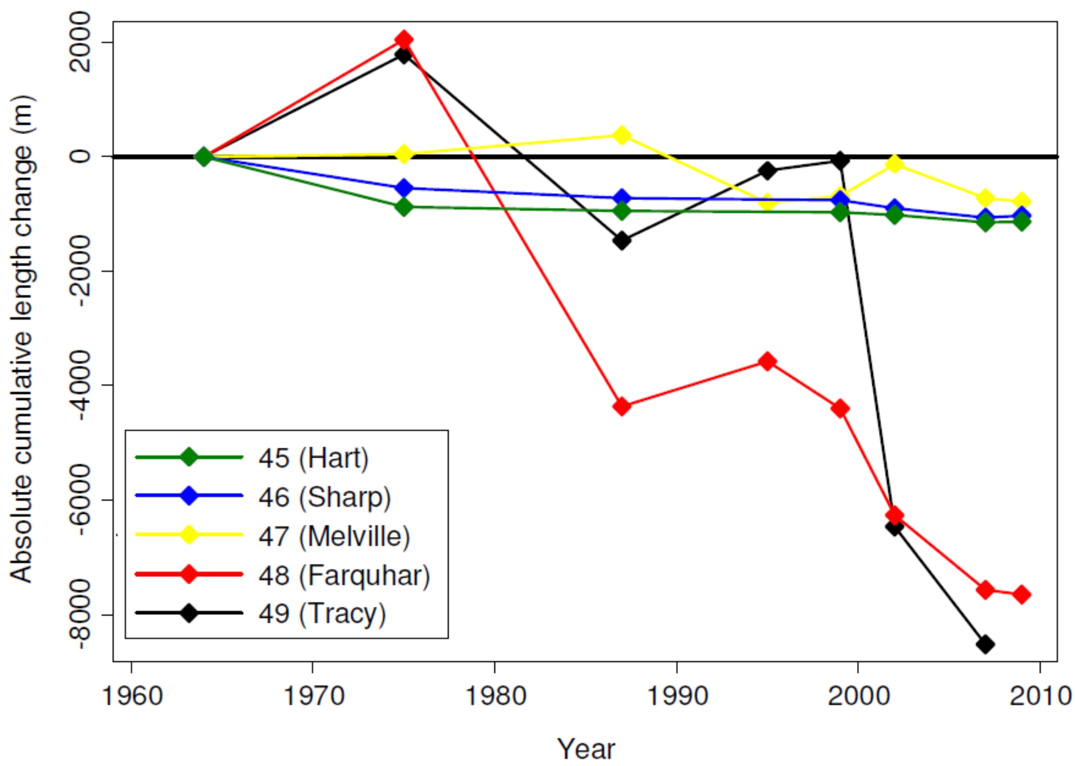


Figure 6.3: Cumulative absolute length change in metres of glaciers 45 to 49 (as shown in Figure 6.3), relative to their position in 1964.

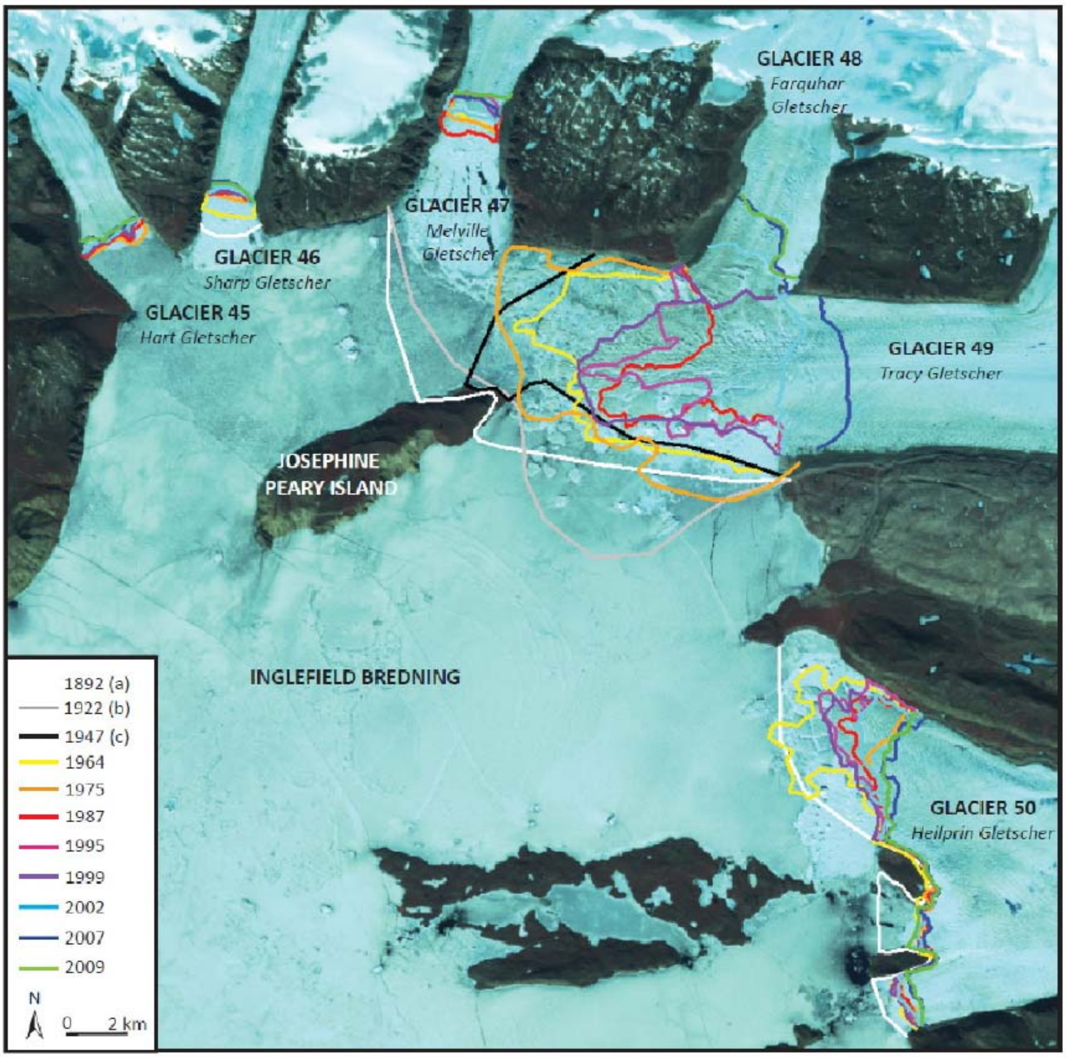


Figure 6.4: Map showing terminus position of Tracy and Heilprin Gletschers at 8 time steps between 1892 and 2009. The coloured lines mark the positions mapped in this study. White line (a) is based on maps by Peary (1893: Plate IV), grey line (b) is based on Dawes and Van As (2010: 81) and black line (c) is based on Kollmeyer (1980: 64). Background is the 1999 Landsat TM base image, displayed using bands 4,3,2 (red, green, blue).

The map produced by Dawes and Van As (2010) is shown in Figure 6.5, and indicates that a slight advance of Tracy Gletscher occurred between 1963 and 1975, a trend that is supported by the data from the present study, which also shows an advance between 1964 and 1975. Dawes and Van As' (2010) map then implies that steady and rapid retreat occurred between 1975 and 2009. However, the more detailed map produced in the present study reveals that this retreat was interrupted by another period of advance between 1987 and 1999. This followed by a period of extremely rapid retreat between 1999 and 2002 as the ice front broke up and both Tracy and

Farquhar Gletschers retreated to the mouths of their respective fjords. Dawes and Van As (2010) concluded that Tracy and Farquhar Gletschers were coalescent between 1892 and 1985, but the more detailed record of terminus positions presented in this study shows that the glaciers were fully coalescent until at least 1999, but had separated by 2002.

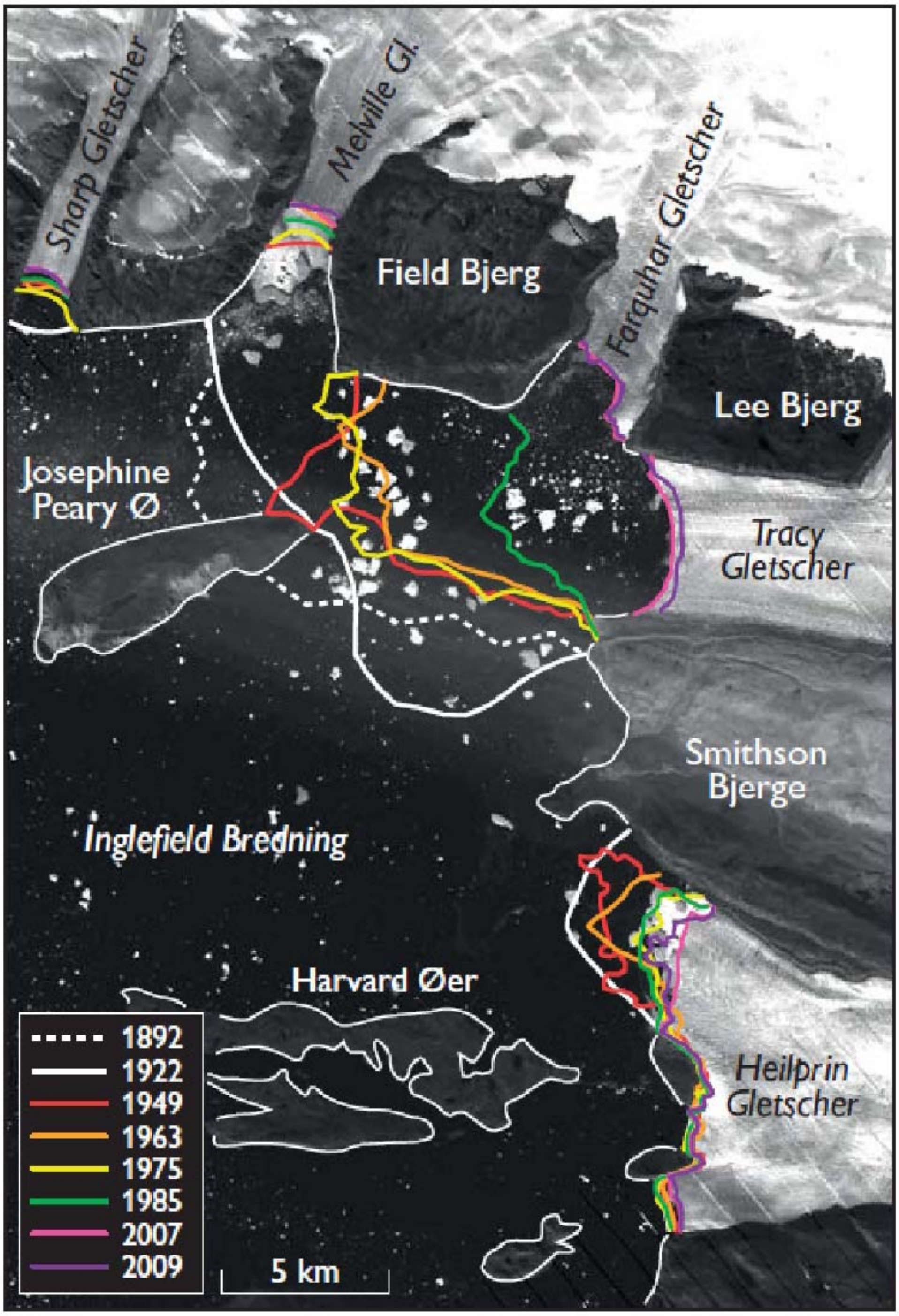


Figure 6.5: Map showing terminus position of Tracy and Heilprin Gletschers at 8 time steps between 1892 and 2009, taken from Dawes and Van As (2010: 81).

When considering the retreat of Heilprin Gletscher, Dawes and Van As' (2010) map indicates that the northern sector of the terminus retreated the furthest distance between 1922 and 2009, at a steady rate. However, the more detailed mapping presented in this study reveals that this retreat was interrupted by a period of advance between 1975 and 1995. The two maps show that Tracy and Heilprin Gletschers have not fluctuated in an identical manner, as Heilprin retreated between 1964 and 1975 whilst Tracy advanced, and *vice versa* between 1975 and 1987. Neighbouring Sharp and Melville Gletschers also demonstrate contrasting behaviour between 1964 and 1975, having retreated and remained stable respectively (Figure 6.4).

Dawes and Van As (2010) suggest that the extensive ice loss exhibited by Melville, Farquhar and Tracy Gletschers is the result of their having floating tongues, which are known to be particularly sensitive to changes in ocean temperature and have often been observed to undergo rapid disintegration (Grove, 1987; Meier and Post, 1987; Csatho et al., 2008). Overall, however, Tracy Gletscher underwent no significant change in terminus position between 1964 and 1999 because retreat was punctuated by periods of advance, as would be expected as part of a tidewater glacier cycle (Meier and Post, 1987). It is not impossible that the recent retreat of glaciers in this region will be followed by further re-advances in the future.

6.3.3 Surge-type glaciers

The only glacier to have been identified as surge-type in the published literature is Harald Moltke Brae (Glacier 59 in this study). This classification has been made based on observations of rapid and significant increases in velocity from 1926-1928, 1937-1938, c. 1956 and c.2005 (Wright, 1939; Mock, 1966; Rignot and Kanagaratnam, 2006). However, detailed records of terminus position are only available for the first half of the century. After the 1960s there is a lack of information on either terminus position or velocity, until the 1990s when short-term assessments of present behaviour were made. The present study has filled this gap by mapping the terminus position of Harald Moltke Brae at seven time steps between 1953 and 2009. In Figure 6.6 these data have been combined with approximate positions of the terminus prior to the 1950s, as reported by Davies and Krinsley (1962).

Overall, Harald Moltke Brae has retreated ~11 km between 1916 and 2009, which equates to 11 % of its original length. During the reported surge of 1926-1928 the glacier advanced by 1.4 km, or 0.47 km a^{-1} (Davies and Krinsley, 1962). The later advance between 1964 and 1972 that is identified in this study was 2.5 km, or 0.3 km a^{-1}. Without measurements of velocity, or more detailed records of terminus position, it is impossible to tell for certain whether the advance from 1964-1972 was a surge. However, of the 11 glaciers in the present study that were measured at 1964 and 1975, only one other (Glacier 48) also advanced during this period. The remaining 10, which included 6 ice sheet outlet glaciers and 5 tidewater glaciers, all retreated. In conclusion, it is quite likely that Harald Moltke Brae surged at some point between 1964 and 1972. Recent velocity measurements indicate that the glacier surged again in c.2005 (Rignot and Kanagaratnam, 2006), but the glacier was only mapped in 1999 and 2007 in this study so changes in terminus position during this surge have not been captured.

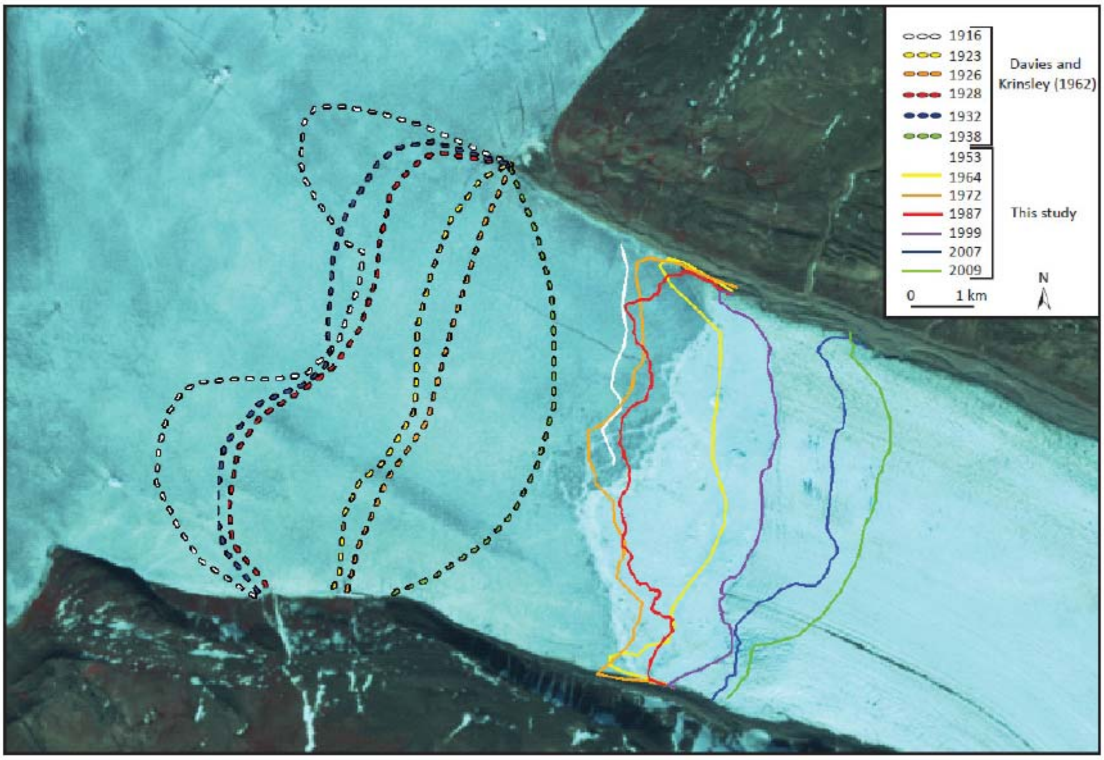


Figure 6.6: Terminus positions of Harald Moltke Brae. The plain coloured lines show position as mapped in this study. The dashed lines are approximate positions as mapped by Davies and Krinsley (1962: 122). Background image is the 1999 Landsat TM base image, displayed as 4,3,2 (red, green, blue) band combination.

Based on the glacier mapping undertaken in this study, Glacier 75 (Berlingske Brae) was also identified as possible surge-type, as it advanced 1.5 km between 1964 and 1987 (Figure 6.7). No other non-surging glacier measured underwent a similar advance during this period, and no other land based glacier has been observed to undergo such rapid advance per year at any other time period. Overall, the mapping indicates that Berlingske Brae advanced ~3.4 km between 1953 and 2009. This unusual behaviour was picked up by Dawes and Van As (2010), who mapped the terminus position at 7 time steps from historical maps, aerial photographs and Landsat images (Figure 6.8). They report that the glacier has advanced 4 km between 1916 and 2009.

Based on the maps of terminus position produced by Dawes and Van As (2010) and the present study, it would appear that Berlingske Brae advanced quite slowly between 1916 and 1964, then advanced large distances each year between 1964 and 1985, before returning to a slightly slower rate of advance between 1985 and 1999. At some point during this latter advance the glacier terminus switched from land-terminating to tidewater as it entered Granville Fjord. Since 1999 the glacier terminus appears to have been virtually stationary, and Dawes and Van As (2010) suggest that the apparent lack of iceberg production implies that it is grounded, rather than afloat. However, the 1999 Landsat base image used for mapping in this study (Figure 6.7) appears to show many icebergs fanning out < 1.3 km from the glacier terminus, which suggests that it has recently calved. The mapped terminus positions for 1999, 2007 and 2009 in this study also show that a section of ice from the southern part of the terminus has broken off, suggesting that the terminus is more dynamic than it would first appear. Neither the present study nor Dawes and Van As (2010) have mapped the terminus position of Berlingske Brae between 1987 and 1999. Unfortunately, no Landsat data covering this glacier during this time period could be found, but it would be very interesting to examine the behaviour of this glacier since the 1980s in more detail in future work, to better understand how it has behaved as a tidewater glacier.

Figure 6.7: Map showing terminus position of Berlingske Brae at 6 time steps between 1953 and 2009. Background image is the 1999 Landsat TM base image, displayed as 4,3,2 (red, green, blue) band combination.

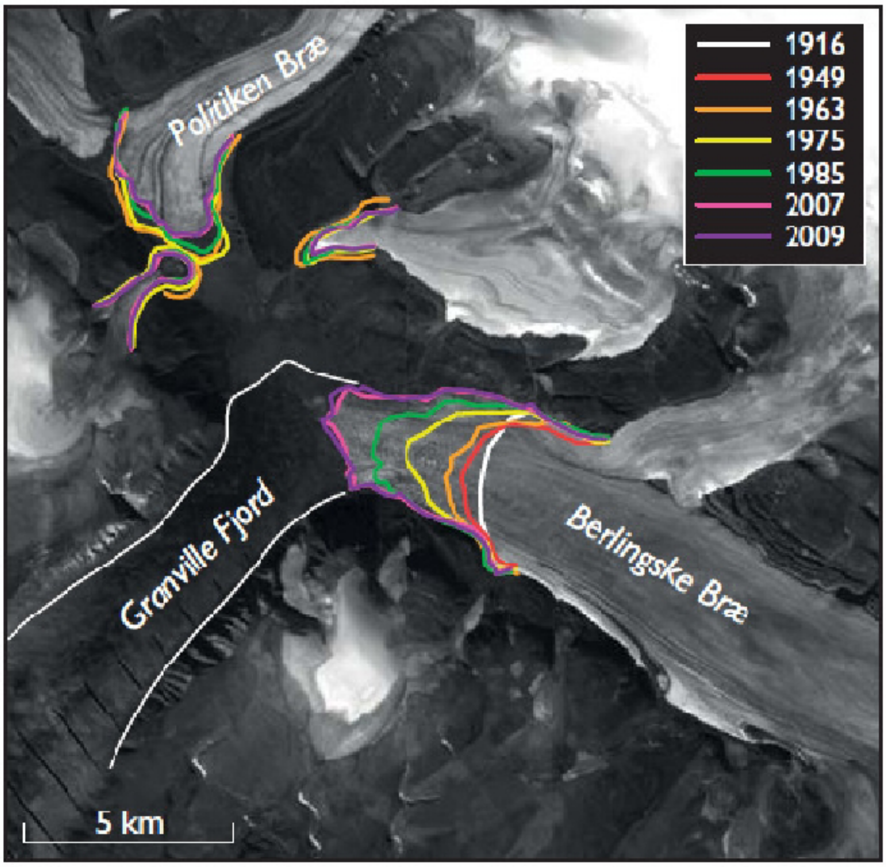


Figure 6.8: Map showing terminus position of Berlingske Brae at 7 time steps between 1916 and 2009, taken from Dawes and Van As (2010: 80).

6.4 Glacier fluctuations in southwest Greenland

6.4.1 Comparison with previous studies of twentieth century length change fluctuations

A detailed survey of 500 West Greenland glacier fluctuations during the first half of the twentieth century was carried out by Weidick (1968). Out of this sample, 135 glaciers had data for the whole of the period from ~1890 to the 1950s, and 49 of those are located within the study area examined here. This sample comprises 9 sections of ice sheet margin, 21 ice cap outlet glaciers and 19 mountain/valley glaciers, and the total absolute retreat data for all of these are shown in Figure 6.9. This map was compiled from the graphs of retreat published for each glacier by Weidick (1968: Plate 2), which he had put together from terminal moraine positions, written descriptions, maps, aerial and terrestrial photographs and field measurements. Weidick (1968) stresses that the written descriptions and maps are not always accurate, so the results for the early twentieth century only give an overview of patterns of retreat.

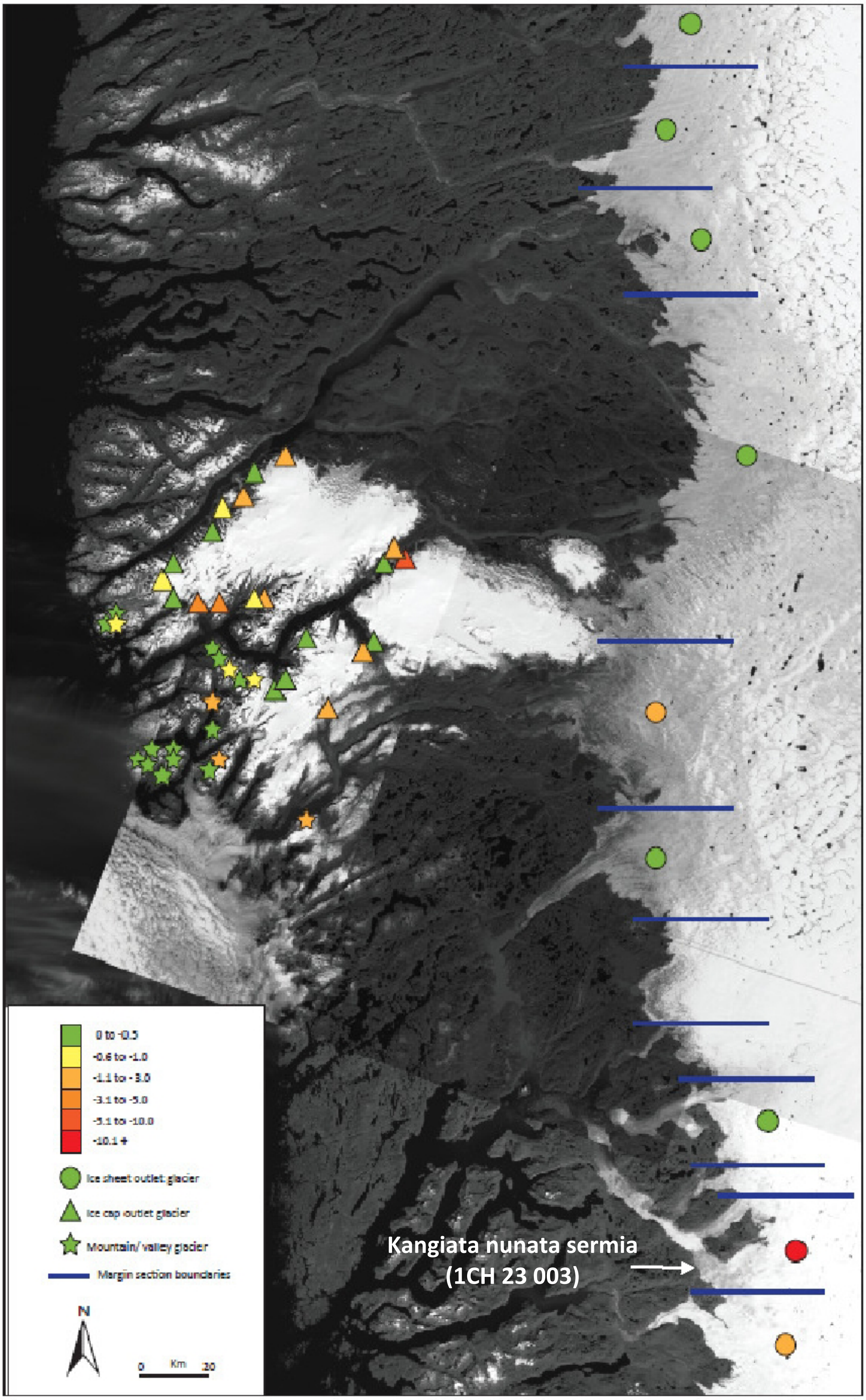


Figure 6.9: Map showing annual glacier retreat as a percentage of overall length between the late 1800s and 1950, based on data compiled by Weidick (1968: Plate 2). Background is the 2001 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

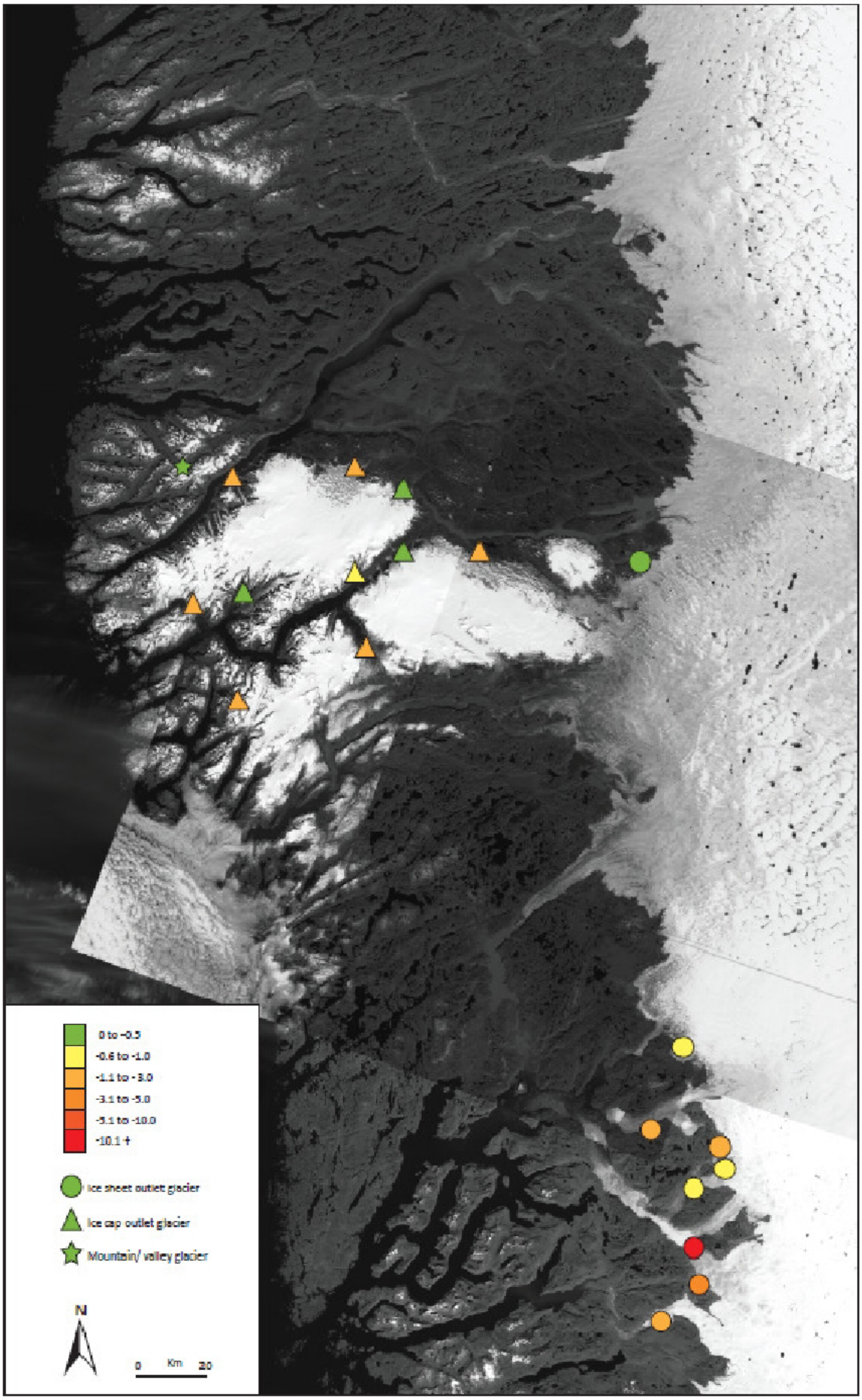


Figure 6.10: Map showing annual glacier retreat as a percentage of overall length between the LIA (1890) and 1964 for glaciers mapped in this study (previously analysed in Chapter 4, Section 4.2.1). Background is the 2001 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

All glaciers mapped by Weidick (1968) in Figure 6.9 retreated or remained stationary between the late 1800s and 1950s, with the majority retreating by no more than 500 metres overall. The most significant retreat was observed for the tidewater ice sheet outlet glacier 1CH 23 003 (Kangiata nunata sermia), which retreated approximately 20 km during this time period. The glacier that retreated the second furthest distance was a land-terminating ice cap outlet glacier, which retreated approximately 6 km. The results are very similar to those of Weidick (1968), with Kangiata nunata sermia undergoing significant retreat of ~12 km between 1890 and 1964 (Figure 6.10). This figure is a minimum estimate of retreat as the position of the glacier terminus during the LIA could only be estimated from the latero-frontal moraines. The data for the ice cap outlet glaciers in the present study are not as numerous as that presented by Weidick (1968), but the pattern of short and long distances retreated is very similar.

The terminal moraines of many more ice cap outlet glaciers were also mapped in the present study, but could not be included in this sample as they could not be accurately mapped from the 1964 imagery. Conversely, data for the ice sheet outlet glaciers for this time period are scarce because many of the glaciers in the study area do not have any obvious terminal moraine limit. Indeed, no obvious moraines were visible for the majority of the ice sheet margin and outlet glaciers north of the Kangiata nunata sermia region. This lack of evidence for any retreat suggests that most of the ice sheet outlet glaciers and ice sheet margins have maintained their positions since the Little Ice Age maximum, or else have retreated and then re-advanced during the twentieth century. This hypothesis is supported by Weidick (1968) who observed that some sections of the ice sheet margin advanced slightly after the 1950s.

Unfortunately, the ice sheet and ice cap margins included in the present study were often found to be difficult to map, primarily due to snow or cloud cover, so there is a lack of detailed data regarding their retreat during most of the twentieth century. However, 7 out of the 11 sections of ice sheet margin measured have advanced between 1987 and 2007/09. The exceptions are sections of 4 margin located around Kangiata nunata sermia (see Chapter 5, Section 5.3.4). Some further information on ice sheet margin changes from c. 1750-1950 and 1950-1985 is provided by Weidick *et* *al.,* (1992; Figure 6.11). The results indicate that the ice sheet margins retreated slightly overall from the LIA to 1950, but that most were re-advancing by 1985.

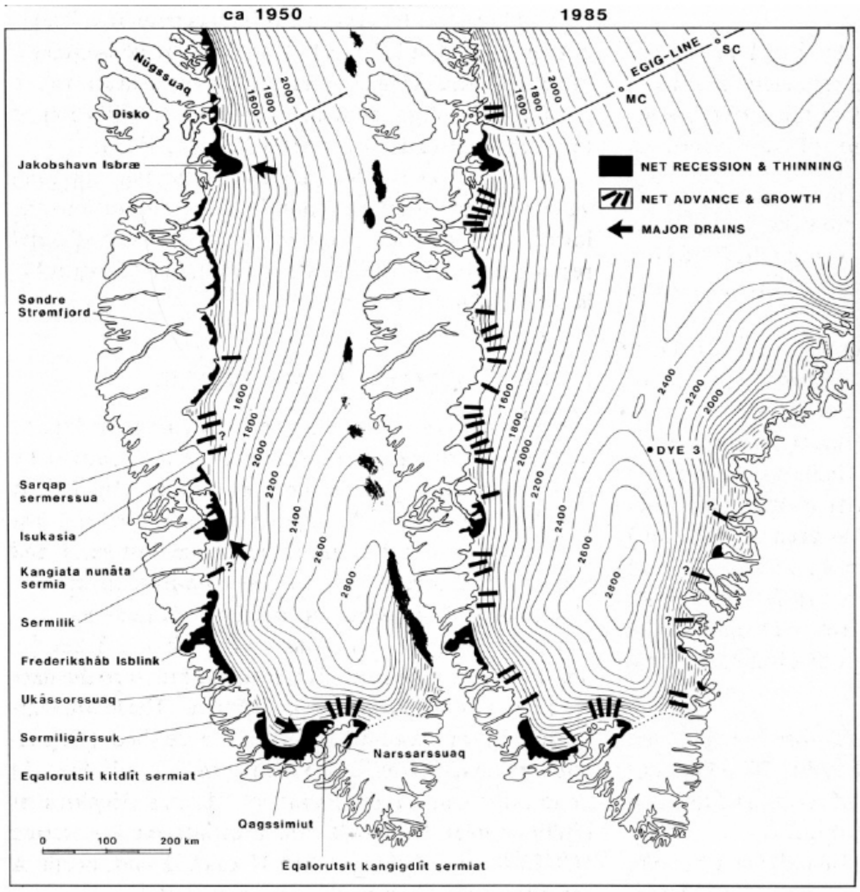


Figure 6.11: Marginal activity in 1950, compared to Little Ice Age (left), and in 1985 compared to 1950 (right). The width of the black zone is an estimate of extent of net thinning and recession. Taken from Weidick *et al.* (1992: 34).

Early twentieth century fluctuations of independent glaciers in the present study area were also investigated by Gordon (1981), who mapped the retreat of 9 mountain/valley glaciers near the Sukkertoppen Ice Cap between 1850 and 1978, based on lichenometric dating of their moraines. The results of Gordon's (1981) study are summarised in Figure 6.12, and they indicate that these glaciers retreated from 1850-1882 to 1942-1968/69, after which the majority advanced or underwent much slower retreat. However, this sample size is extremely small and is based on glaciers of one class in one tiny coastal area of Greenland, so is not necessarily representative of the behaviour of all glaciers in this region. The results do support the rapid retreat from 1943-1964, then advance from 1964-1973, that was reported for ice cap outlet glaciers in the present study (see Chapter 5, Section 5.3.3).

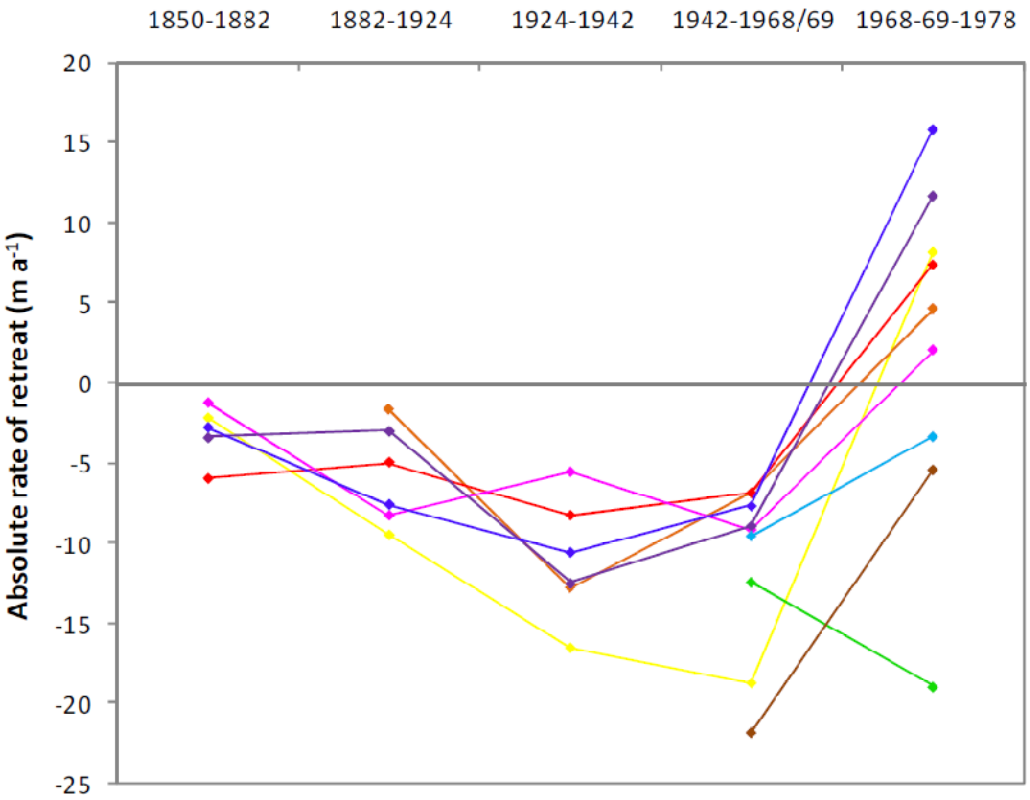


Figure 6.12: Absolute distance retreated per year for 9 mountain/ valley glaciers located near the Sukkertoppen Ice Cap, between 1850 and 1978. Data taken from a study by Gordon (1981:54), based on lichenometric dating of terminal moraines.

Citterio *et al.* (2009) have recently investigated spatial patterns of ice cap and mountain glacier retreat for the area around around Disko Island in Central West Greenland (north of the southwest study area). They concluded that glaciers closest to the sea decreased in area more than those located further inland, between the LIA and 2001 (Figure 6.13). In particular, those glaciers located nearest to the Greenland ice sheet have undergone very little change in area, and the authors suggest that this is due to the drier and colder climate in this region.

Given the evidence presented by Citterio *et al.* (2009), independent ice cap and mountain glaciers near the coast in the present study might be expected to have retreated further than those inland. However, no such trend was observed, and all independent glaciers retreated at similar rates overall. This is unexpected, given that and they are located across an area 150 km long, between the coast and the ice sheet, and that air temperature and precipitation are significantly higher at the coast compared to inland (see Chapter 5, Section 5.2). The uniform retreat of the ice cap and mountain glaciers suggests, therefore, that temperatures and precipitation have changed by a similar magnitude throughout the whole of the southwest region during the twentieth century.

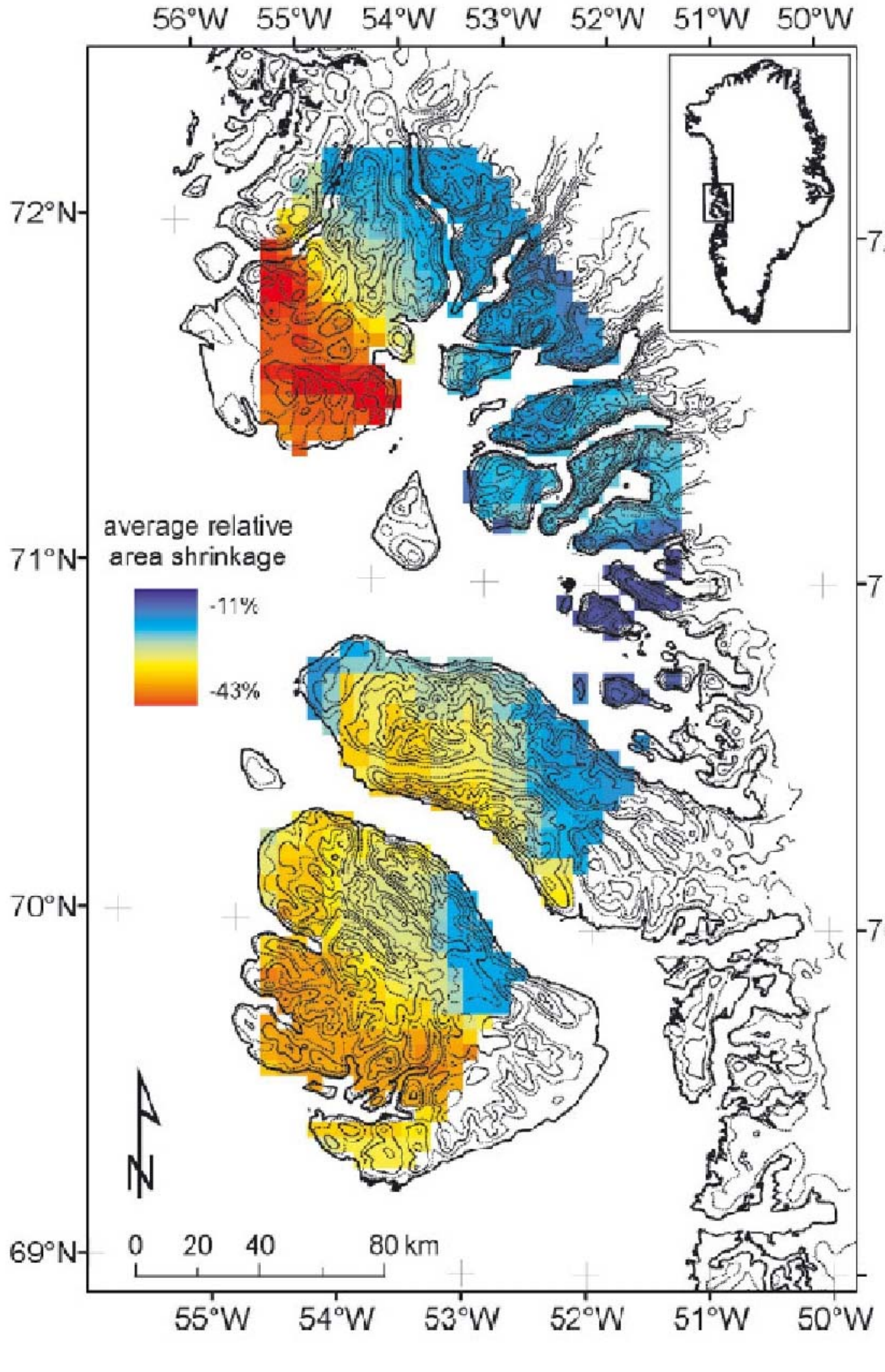


Figure 6.13: Spatial patterns of relative area change between the LIA and 2001 of glaciers on Disko Island and the Nuussuaq and Svartenhuk peninsulas in Central West Greenland. Variability is shown as a 50 km x 50 km average. Map was produced by Citterio *et al.* (2009: 76).

6.5 Regional glacier fluctuations: a comparison

In this section, the most notable differences in glacier behaviour between the northwest and southwest study areas are first discussed in Sections 6.4.1 and 6.4.2. Glacier length changes are then compared to length change data from other regions of Greenland in Section 6.4.3.

6.5.1 Differences in the patterns of retreat rates over time

Calculations of decadal rates of length change for all glaciers indicated that rates had fluctuated between small and large distances retreated in the northwest, but increased steadily from slow advance to moderate retreat over time in the southwest (see Chapter 4, Section 4.2.3). In the northwest, the majority of ice sheet outlets and independent glaciers are tidewater, whereas in the southwest the ice sheet outlet glaciers and most independent glaciers are land-terminating. Examination of glaciers with different terminus environments revealed that tidewater glaciers fluctuated in rate of retreat, whereas land-terminating glaciers underwent only small changes in rate of length change from decade to decade (see Chapter 5, Section 5.3.3). This explains the different overall retreat patterns.

6.5.2 Differences in the distances retreated during the twentieth century

The most striking difference between the two regions is that glaciers of all classes in the northwest have retreated further than those in the southwest over the whole period since the Little Ice Age, and also at most shorter time steps. This result is particularly unexpected when put into context with data on whole ice sheet changes during the past two decades, which indicate that the ice sheet margins have been losing mass and thinning rapidly since the 1990s in the south, but that this trend did not spread to the north until the mid-2000s (Pritchard *et al.,* 2009; Velicogna, 2009; Khan *et al.,* 2010; see Chapter 2, Section 2.3.3). However, a recent map of mass balance changes between 2003 and 2008 suggests that the northwest lost a larger proportion of its mass through ice discharge compared to the southwest (Van den Broeke *et al.,* 2009; see Chapter 2, Figure 2.11), which supports the greater retreat of northwest glaciers that was revealed by the present study.

Previous studies have found that tidewater glaciers in other regions of Greenland have generally retreated faster than neighbouring land-terminating glaciers during the past two decades (Howat *et al.,* 2008; Moon and Joughin, 2008). As noted in Section 6.5.1 above, the northwest region has many more tidewater ice sheet outlets and independent glaciers than the southwest, and this could explain the more extensive retreat observed in the present study. However, the data on glacier fluctuations by terminus environment (Chapter 5, Section 5.4) revealed that tidewater glaciers have not retreated significantly further overall than land-terminating glaciers during the twentieth century in either study area, thus contradicting this hypothesis.

The differences in rates of retreat could instead be the result of differences in regional climate, because whilst the southwest has higher air temperatures it also receives more precipitation. In particular, this difference may explain the greater rate of retreat in the northwest since 1999. Air temperatures in both regions have increased by approximately 2°C since the 1990s, but the effects in the southwest may have been partially mitigated by the increase in precipitation during this period. This hypothesis would also explain why glaciers of all classes and terminus environments in the southwest have retreated more slowly than their counterparts in the northwest.

In Section 6.2.2, further hypotheses were put forward to explain the prolonged advance of the ice sheet margins and outlet glaciers in the southwest, and Huybrechts (1994) suggested that this behaviour could be a long-term response to the last glacial-interglacial transition. The proximity of the ice sheet margin to the coastline in the northwest may have prevented it from behaving in a similar way as there is no room for advance (Huybrechts, 1994). However, this does not explain why the ice sheet outlet glaciers have not advanced, or why the independent ice caps and mountain glaciers have retreated further than their counterparts in the southwest.

Alternatively, it has been suggested that the advance of the ice sheet in the southwest may be partly due to increased surface melting after air temperatures increased, which led to basal lubrication and increased sliding (Zwally et al., 2002; Parizek and Alley, 2004; see Section 6.2.2). This mechanism would be less effective in the northwest because the ice sheet has a much steeper surface slope, so the ablation area is consequently much smaller. A map showing overall ice sheet mass balance between 1957 and 2007 was presented in Chapter 2, Figure 2.9 (Ettema *et al.,* 2009). This showed that the southwest sector of the ice sheet had lost mass over a larger area than the northern sector, which supports the hypothesis that advance is the result of more meltwater reaching the bed.

There are some problems with this hypothesis, however. Firstly, Pritchard *et al.,* (2009) have produced a map of surface elevation changes around the ice sheet between 2003 and 2007 (Figure 6.14), which indicates that the northwest margins thinned significantly during this period but the southwest did not. If the ice sheet margin were still advancing in the southwest, we would expect it to be thinning (Parizek and Alley, 2004). Secondly, this hypothesis does not explain why independent glaciers in the southwest advanced from 1964 until approximately 1987.

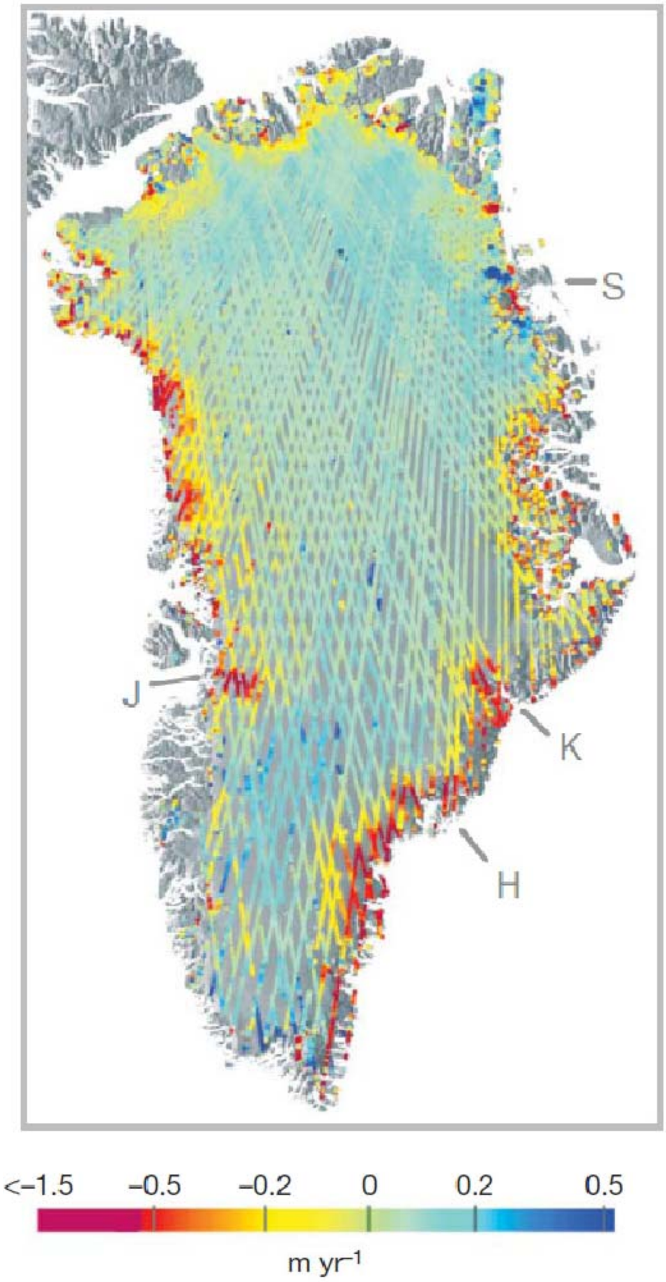


Figure 6.14: Rate of change of surface elevation for the Greenland Ice Sheet between 2003 and 2007 (Pritchard *et al.,* 2009:3)

6.5.3 Regional glacier fluctuations in context with Greenland length changes

Previous research into glacier length changes in all regions of Greenland during the twentieth century was reviewed in Chapter 2 (Section 2.3) and a summary of past fluctuations is given in Table 6.2. The most important point to arise from this is that the advance of the ice sheet outlet glaciers and margins in the southwest during the latter half of the twentieth century is not unique, as advances have also been recorded in the Southwest and Central West, and also to some extent the Southern East regions of Greenland (Weidick, 1959; 1968; 1995; 2009). However, advance in these regions appears to have been confined to small areas of margin, whereas in the southwest the entire section of ice sheet advanced (~332 km), with the exception of the region around Kangiata nunata sermia. All these regions of the ice sheet appear to have started advancing around the same time, during the 1950s and 1960s suggesting a common trigger, most likely a change in air temperature or precipitation. It would be interesting to compare whether the glaciers in all regions stopped advancing at a similar time as well, but this is not possible due to lack of observations.

Ice sheet outlet glaciers in several regions of Greenland appear to have undergone relatively rapid retreat during the first half of the twentieth century. This matches the extensive retreat observed in the southwest and northwest of the present study suggesting a common cause, which is most likely to be the general increase in air temperatures observed during the first half of the century (see Chapter 2, Section 2.5.1).

Recently, Moon and Joughin (2008) measured the retreat of all ice sheet outlet glaciers in Greenland with a terminus wider than 2 km between 1992 and 2007. The majority of these glaciers were tidewater, and those that were measured at several time steps are shown in Figure 6.15. This sample does not include any glaciers in the southwest, but those in the northwest study area have not retreated as far on average as those slightly further down the coast in Northern West Greenland. These regions are very similar, in that the margin is very close to the coast and a lot of the outlet glaciers are tidewater (Weidick, 1995). However, the Northern West region is further south, so likely has warmer air and sea surface temperatures, which might explain why glaciers have retreated further in recent years.

Region	Description of 20th century behavior: ice sheet	Description of 20th century behavior: independent glaciers	References
Southwest	Most sectors of ice sheet margin have retreated throughout the twentieth century, but the area around Eqalorutsit kangigdlit sermiat has advanced beyond its LIA maximum position. In general, retreat was most rapid 1920-1940.	Fast retreat between 1920 and 1940.	Weidick (1959; 1968; 1995; 2009)
Southern West	The area of margin around Kangiata nunata sermia has retreated significantly since the 1800s. Further north, most of the ice sheet margin and outlet glaciers retreated during the first half of the 20th century, most rapidly between 1920 and 1940, but have been advancing since at least the 1960s.	General recession since 1890, which was particularly fast 1920-1950s. Many glaciers readvanced after the 1950s.	Weidick (1959; 1968; 1995)
Central West	Glaciers around Disko Bugt are main calf ice producers for West Greenland. Sections of margin either side of Jakobshaven Isbrae were stationary < 1960s, then advanced slightly. Tidewater outlet glaciers have retreated overall throughout the 20th century. Some land glaciers have readvanced during the 1950s.	Independent ice caps on Disko Island have retreated overall during 20th century.	Kollmeyer (1980); Weidick (1994; 1995); Sohn *et al.* (1998)
Northern West	Lots of tidewater ice sheet outlet glaciers, whose termini have fluctuated extensively. Many have retreated significantly since the 1980s.	Virtually no independent glaciers.	Weidick (1995)
Northwest	Majority of glaciers have retreated overall, with the Brother John Gletscher the only one to have advanced significantly overall. Some others may have advanced briefly during the 1950s.	North Ice Cap expanded up until at least the 1960s. Majority of glaciers retreated throughout first half of 20th century.	Davies and Krinsley (1962); Weidick (1994; 1995)

Northern Greenland	Ice sheet outlet glaciers appear to have been very stable up until at least the 1960s, but have not been extensively studied.	Glaciers generally very stable until at least 1956. Only ~18 % retreating.	Davies and Krinsley (1962); Weidick (1995)
Northeast	Mixture of stationary and retreating outlet glaciers between LIA and 1956.	No glaciers observed to retreat between LIA and 1956.	Davies and Krinsley (1962); Weidick (1995)
Northern East			
Central East	Very little retreat. Glaciers have remained stable since at least the 1950s.	Very little retreat.	Weidick (1995); Stearns *et al.* (2005); Stearns and Hamilton (2006)
Southern East	Outlet glaciers retreated up to 4 km in some cases, whereas others have advanced. Most of the ice sheet margin was stable 1930s to 1990s.		Dwyer (1995); Weidick (1995)
Southeast	Most ice sheet outlets retreated significantly throughout whole century.	Very few independent glaciers.	Weidick (1995)

Table 6.2: Summary of the behaviour of the Greenland Ice Sheet and independent ice caps during the twentieth century, as reported in the literature; see Chapter 2 (Sections 2.3 and 2.4) for more details.

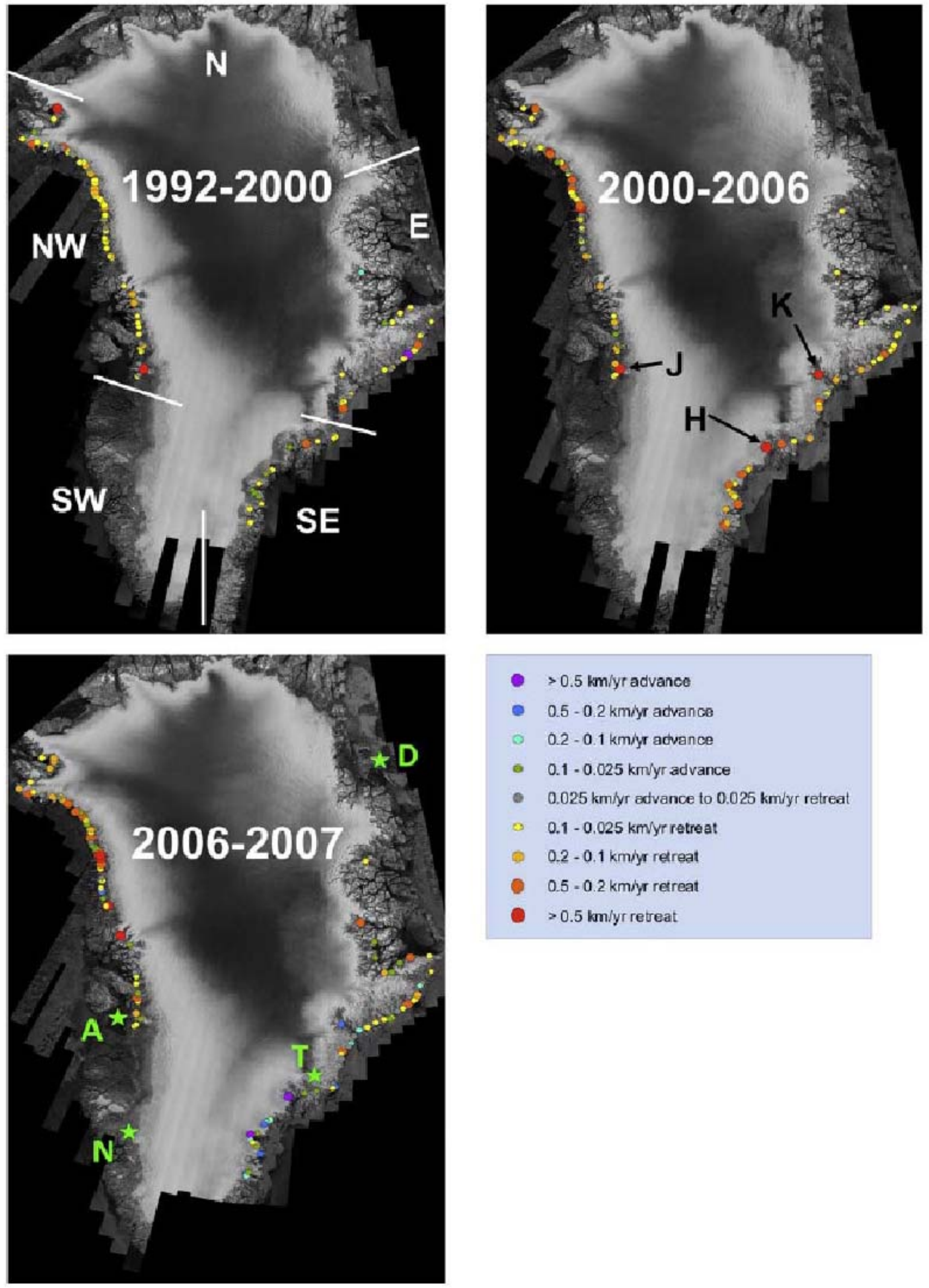


Figure 6.15 Retreat (red/yellow) and advance (blue/green) of 122 large ice sheet outlet glaciers (predominantly tidewater) measured at all four time steps between 1996 and 2007 by Moon and Joughin (2008: 3).

6.6 Limitations of the study

Some factors that have limited the conclusions that can be drawn from the data presented in this study are identified below. These predominantly arise from a lack of suitable image data, so would be difficult to rectify. However, some potential avenues of future investigation are identified. The four main limitations of this study are:

1. **The lack of image data for the first half of the twentieth century.**

   Satellite imagery is only available for the 1960s onwards and aerial photographs were very costly and time-consuming to process, so only a few glaciers could be mapped between the LIA and 1964. In future work, it would be interesting to examine this period in more detail using aerial photographs, in order to better understand how glaciers responded to the rapid rise in air temperatures after the 1920s.

2. **A lack of high-quality images to cover the whole study area for every year prevented glaciers from being mapped at every time step.**

   This was a particular problem when mapping changes during the 1970s and 1980s, as only a limited number of Landsat images were available and these were often taken early in the year when snow obscured many of the glaciers. Because not all glaciers could be mapped at every time step this meant that decadal analysis was based on a very small sample of glaciers, so the results are not conclusive. This problem could be rectified with the use of aerial photographs from the 1980s, but this would be costly and time consuming.

3. **There is no information on surface elevation, mass balance or volume changes.**

   Terminus position is not always a reliable indicator of the overall response of a glacier to climate change. For example, the terminus of a glacier may be advancing yet the glacier overall be thinning as a result of surface mass loss. However, reconstructing these changes for large numbers of glaciers during the whole of the twentieth century is extremely difficult.

4. **Glaciers were not mapped at enough time steps to allow lag times to be quantified.**

   It was not possible to accurately quantify glacier lag times in this study, partly because glacier samples were quite small, and partly because measurements were generally only made every decade. Mapping more glaciers at more time steps would aid the calculation of the lag times of different glacier classes and terminus environments. However, future work in this direction is very limited due to the lack of suitable satellite imagery over longer time scales (see point 1).

Chapter 7

Conclusions

In this study, the terminus positions of glaciers of all classes and terminus environments in northwest and southwest Greenland have been mapped at a number of time steps from the Little Ice Age to 2009. These data have been analysed in conjunction with regional climate records, to determine what factors influence length changes and examine differences in behaviour between northwest and southwest Greenland. Based on this analysis, five key conclusions can be drawn:

1. **Glacier length changes in northwest and southwest Greenland appear to have been driven by air temperature changes and moderated by precipitation.**
   Periods of rapid rates of glacier retreat appear to correlate to periods of warmer air temperatures in both the northwest and southwest study areas. Glaciers seem to have responded to significant temperature shifts within a decade, although the actual lag time is likely to vary between different classes and terminus environments. Temperatures in both the northwest and southwest have increased sharply since c.1990, and this has been matched by an increase in retreat of most glacier classes since 1999/2001. This increase has been less marked in the southwest, however, and may have been partially offset by the concurrent increase in precipitation.

2. **Tidewater glaciers have not retreated significantly further than land-terminating glaciers during the twentieth century.**
   Some recent studies of Greenland Ice Sheet outlet glacier fluctuations have found that land-terminating glaciers have retreated more slowly than tidewater glaciers during the past two decades. The results of the present study indicate that tidewater glaciers fluctuate between fast and slow retreat at the decadal and two-decade time scale, but that overall they have retreated similar distances to land-terminating glaciers in absolute terms, and often shorter distances in relative terms.

Recent research has tended to focus on glacier fluctuations since the 1990s, and many tidewater glaciers have been observed to accelerate during this time period. Data from the present study indicate that recent rapid retreat of southwest glaciers is not unprecedented, as they appear to have retreated greater distances during the 1940s and 1950s compared to the 2000s. These results highlight the need for more investigation into the fluctuations of both land-terminating and tidewater glaciers over longer time scales. In particular, more detailed investigations of aerial photographs and historical observations from the first half of the twentieth century will give us a better understanding of how glaciers have responded to significant temperature increases in the past, and thus determine how they may respond in the future.

3. **Glaciers in different classes have retreated at significantly different rates during the twentieth century.**

   Ice sheet margins underwent much smaller amounts of advance or retreat than any other class in both absolute and relative terms during the second half of the twentieth century. Furthermore, ice sheet outlet glaciers were observed to retreat significantly shorter distances as a proportion of their overall length than the neighbouring independent ice caps and mountain/valley glaciers. These independent glaciers could potentially make a small but significant contribution to global sea level rise if they were to continue melting and retreating. However, there is very little up-to-date information in the published literature on how these glaciers have responded to either past or present climate change in most regions of Greenland, so much more research is required.

4. **Ice sheet margins and outlet glaciers in the southwest advanced steadily between 1964 and 2001 and have not retreated significantly since then.**

   Two hypotheses have previously been put forward to explain this behaviour. The first is that this sector of the ice sheet is still adjusting to rapid retreat that occurred during the last glacial-interglacial transition, and the second is that increased surface melting has led to basal lubrication and increased sliding.

However, neither of these hypotheses can convincingly explain the advance of many independent glaciers in southwest Greenland from ~1964 to ~1987 that was identified in the present study.

5. **Glaciers in the northwest have consistently retreated further than those in the southwest, at all time periods.**

   This pattern was observed for all glacier classes, terminus environments and samples, and is most probably a consequence of differences in regional climate. Temperatures are lower in the northwest than in the southwest, but any increase is likely to have more effect as it also receives less precipitation than the southwest. Alternatively, this behaviour could be due to other factors, such as the northwest having more tidewater glaciers. However, tidewater glaciers were shown to have retreated similar distances to land glaciers overall so this explanation cannot be correct. Differences in regional climate would explain why both ice sheet outlet glaciers and independent glaciers have retreated further in the northwest than in the southwest.

Chapter 8

References

Abdalati, W., Krabill, W., Frederick, E. Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W. and Yungel, J., (2001), “Outlet glacier and margin elevation changes: near-coastal thinning of the Greenland ice sheet”, *Journal of geophysical research* 106(D24): 33729-33741

Altmaier, A. and Kany, C., (2002), “Digital surface model generation from CORONA satellite images”, *Journal of photogrammetry and remote sensing* 56: 221-235

Bahr, D.B., Pfeffer, W.T., Sassolas, C. and Meier, M.F.,(1998), “ Response time of glaciers as a function of size and mass balance: I. theory”, *Journal of Geophysical Research* 103(B5): 9777-9782

Barry, R.G., (2006), “The status of research on glaciers and global glacier recession: a review”, *Progress in physical geography* 30: 285-306

Bell, R., (2008), "The role of subglacial water in ice-sheet mass balance", *Nature geoscience* 1: 297-304

Beschel, R. E. and Weidick, A., (1973), "Geobotanical and geomorphological reconnaissance in West Greenland, 1961", *Arctic and Alpine Research* 5(4): 311-319

Blake, W., (1999), "Glaciated Landscapes Along Smith Sound, Ellesmere Island, Canada and Greenland", *Annals of Glaciology* 28: 40-46

Bolch, T., Buchroithner, M., Pieczonka, T. and Kunert, A., (2008), “Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using CORONA, Landsat TM and ASTER data”, *Journal of glaciology* 54(187): 592-600

Box, J. E., (2002), "Survey of Greenland instrumental temperature records, 1873-2001", *International journal of climatology* 22: 1829-47

Box, J.E., (2009), “Greenland glaciers continue to lose ice area”. Available online from: http://bprc.osu.edu/wiki/Jason_Box_Homepage [last accessed 06/12/09]

Box, J.E., Yang, L., Bromwich, D.H. and Bai, L., (2009), “Greenland Ice Sheet surface air temperature variability: 1840-2007”, *Journal of climate* 22: 4029-4049

Braithwaite, R.J., (2009), “After six decades of monitoring glacier mass balance we still need data but it should be richer data”, *Annals of glaciology* 50(50): 191-197

Braithwaite, R.J. and Olesen, O.B., (1993), "Seasonal variation of ice ablation at the margin of the Greenland ice sheet and its sensitivity to climate change, Qamanrssp sermia, West Greenland", *Journal of glaciology* 39(132): 267-274

Bromwich, D.H. and Nicolas, J.P., (2010), "Sea-level rise: ice sheet uncertainty", *Nature geoscience* 3: 596-597

Buch, E., (2000), "A monograph on the physical oceanography of the Greenland waters", *DMI scientific report 00-12*

Buch, E., (2002), "Present oceanographic conditions in Greenland waters", *DMI scientific report 02-02*

Bull, C., (1963), "Glaciological reconnaissance of the Sukkertoppen ice cap, south-west Greenland", *Journal of glaciology* 4: 813-816

Burgess, D.O. and Sharp, M.J., (2004), "Recent changes in areal extent of the Devon Ice Cap, Nunavut, Canada", *Arctic, Antarctic and Alpine research* 63(2): 261-271

Cappelen, J., (2006), "DMI annual climate data collection 1873-2005, Denmark, The Faroe Islands and Greenland", *DMI Technical report 06-08*

Carstensen, L.S. and Jorgensen, B.V., (2010), "Weather and climate data from Greenland 1958-2009", *DMI Technical report 10-08*

Citterio M., Paul, F., Ahlstrom, A.P., Jepsen, H.F. and Weidick A., (2009), "Remote sensing of glacier change in West Greenland: accounting for the occurrence of surge-type glaciers", Annals of glaciology 50(53): 70-80

Chamberlin, T.C., (1897), "Glacial studies in Greenland", *Journal of geology* 5

Church, J.A. and White, N.J., (2006), "A 20th century acceleration in global sea-level rise", *Geophysical research letters* 33: L01602

Clarke, G.K.C., (1991), "Length, width and slope influences on glacier surging", *Journal of glaciology* 37(126): 236–246.

Cook, A.J., Fox, A.J., Vaughan, D.G. and Ferrigno, J.G., (2005), "Retreating glacier fronts on the Antarctic Peninsula over the past half-century", *Science* 308: 541-544

Copland, L., Sharp, M.J. and Dowdeswell, J.A., (2003), “The distribution and flow characteristics of surge-type glaciers in the Canadian High Arctic”, *Annals of glaciology* 36: 73–81

Csatho, B., Schenk, T., Van der Ween, C.J. and Krabill, W.B., (2008), "Intermittent thinning of Jakobshavn Isbrae, West Greenland, since the Little Ice Age", *Journal of glaciology* 54(184): 131-144

Davies, W. E. and Krinsley, D.B., (1962), "The recent regimen of the ice cap margin in North Greenland", *International Association of scientific hydrology* 58: 119-130

Dawes, P.R. and van As, D., (2010), “An advancing glacier in a recessive ice regime: Berlingske Brae, Northwest Greenland”, *Geological survey of Denmark and Greenland Bulletin* 20: 79-82

DeBeer, C.M. and Sharp, M.J., (2007), “Recent changes in glacier area and volume within the southern Canadian Cordillera”, *Annals of glaciology* 46: 215-221

Douglas, B.C., Cheney, R.E., Miller, L., Agreen, R.W., Carter, W.E. and Robertson, D.S., (1990), “Greenland Ice Sheet- is it growing or shrinking?”, *Science* 248(4953): 288

Dowdeswell, J.A., (1995), “Glaciers in the High Arctic and recent environmental change”, *Philosophical transactions of the Royal Society of London A* 352(1699): 321-334

Dowdeswell, J.A., Hagen, J.O., Bjornsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., Koerner, R.M., Lefauconnier, B., Ommanney, C.S.L. and Thomas, R.H., (1997), “ The mass balance of circum-Arctic glaciers and recent change”, *Quaternary research* 48(1): 1-14

Dwyer, J. L., (1995), "Mapping tide-water glacier dynamics in east Greenland using Landsat data”, *Journal of Glaciology* 41(139): 584-595

Dyurgerov, M.B. and Meier, M.F., (1997a), “Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea-level changes”, *Arctic and Alpine research* 29(4): 392-402

Dyurgerov, M.B. and Meier, M.F., (1997b), “Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea level changes”, *Arctic and Alpine research* 29(4): 392-402

Dyurgerov, M.B. and Meier, M.F., (2005), "Glaciers and the changing Earth system: a 2004 snapshot", *Institute of Arctic and Alpine research occasional paper* 58, University of Colorado

ERSDAC, (2009), "ASTER global digital elevation model: features". Available online from: http://www.ersdac.or.jp/GDEM/E/2.html [Last accessed 12/08/2010]

Ettema, J., van den Broeke, M.R., van Meijgaard, E., van de Berg, W.J., Bamber, J.L., Box, J.E. and Bales, R.C., (2009), "Higher surface mass balance of the Greenland ice sheet revealed by high resolution climate modelling", *Geophysical research letters* 36: L12501

Fettweis, X., Hanna, E., Gallee, H., Huybrecht, P. And Erpicum, M., (2008), "Estimation of the Greenland ice sheet surface mass balance during the 20th and 21st centuries", *The cryosphere discussions* 2: 225-254

GLIMS (2008), "More about GLIMS". Accessed online at: www.glims.org/About [last accessed 13/09/2010]

Goldthwait, R.P., (1960), "Study of an ice cliff in Nunatarssuaq Greenland", Cold Regions Research and Engineering Laboratory, technical report 39

Goldthwait, R.P., (1961), "Regimen of an ice cliff on land in northwest Greenland", *Folia geografika Danica* IX: 107-115

Goldthwait, R.P., (1971), "Restudy of Red Rock ice cliff, Nunatarssuaq, Greenland", Cold Regions Research and Engineering Laboratory, technical report 224

Gordon, J. E., (1981), "Glacier margin fluctuations during the 19th and 20th centuries in the Ikamiut Kangerdluarssuat area, west Greenland", *Arctic and Alpine Research* 13(1): 47-62

Grant, K.L., Stokes, C.R. and Evans, I.S., (2009), "Identification and characteristics of surge-type glaciers on Novaya Zemlya, Russian Arctic", *Journal of glaciology* 55(194): 960-972

Grove, J.M., (1987), "Glacier fluctuations and hazards", *The geographical journal* 153(3): 351-367

Haeberli, W., (1998), “Historical evolution and operational aspects of worldwide glacier monitoring”. In: Haeberli, W., Hoelzle, M. and Suter, S. (eds.), “Into the second century of worldwide glacier monitoring: prospects and strategies”, *Studies and reports in hydrology*, Paris, UNESCO publishing: 35-52

Hall, D.K., Chang, A.T.C., Foster, J.L., Benson, C.S. and Kovalick, W.M., (1989), “Comparison of *in situ* and Landsat derived reflectance of Alaskan glaciers”, *Remote sensing of environment* 28: 23-31

Hall, D. K., Bahr, K.J., Shoener, W., Bindschandler, R.A. and Chien, J.Y.L., (2003), "Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space", *Remote Sensing of Environment* 86: 566-577

Hanna, E., Huybrechts, P., Janssens, I., Cappelen, J., Steffen, K. and Stephens, A., (2005), Runoff and mass balance of the Greenland ice sheet: 1958-2003, *Journal of geophysical research* 110: D13108

Hanna, E., Cappelen, J., Fettweis, X., Huybrechts, P., Luckman, A. And Ribergaard, M.H., (2009), “Hydrologic response of the Greenland ice sheet: the role of oceanographic warming”, *Hydrological processes* 23: 7-23

Haynes, V.M., (1972), “The relationship between the drainage areas and sizes of outlet troughs of the Sukkertoppen Ice Cap, West Greenland”, *Geografiska annaler, series A, 54(2): 66-75*

Henry, T.A. and White, R.J., (1964), “The temperature of the Sukkertoppen ice cap”, *Journal of glaciology* 5: 265-267

Hock, R., de Woul, M., Radic, V. and Dyurgerov, M., (2009), “Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution”, *Geophysical research letters* 36: L0750

Holland, D.M., Thomas, R.H., De Young, B., Ribergaard, M.H. and Lyberth, B., (2008), “Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters”, *Nature geosciences* 1(10): 659-664

Holm, G.F., (1883), “Geographisk undersogelse af Gronlands sydlieste Del 1881”, *Meddelelser om Gronland* 6

Howat, I. M., Joughin, I., Fahnestock, M., Smith, B.E. and Scambos, T.A., (2008), "Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000-06: ice dynamics and coupling to climate", *Journal of Glaciology* 54(187): 646-660

Huybrects, P., (1994), "The present evolution of the Greenland ice sheet: an assessment by modelling", *Global and planetary change* 9: 39-51

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed.. Solomon.S et al., Cambridge Univ. Press, Cambridge, U. K., available at http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

Jiskoot H., Curran C.M., Tessler D.L. and Shenton L.R., (2009), "Changes in Clemenceau Icefield and Chaba Group glaciers, Canada, related to hypsometry, tributary detachment, length-slope and area-aspect relations", *Annals of glaciology* 50(53): 133–143

Jóhannesson, T., Raymond, C. F., and Waddington, E. D., (1989), "A simple method for determining the response time of glaciers". In: J. Oerlemans (ed.), Glacier fluctuations and climatic change, Dordrecht, Kluwer Academic Publishers: 343-352

Joughin, I., (2006), "Greenland rumbles louder as glaciers accelerate", *Science* 311(5768): 1719-1720

Joughin, I., Abdalati, W. and Fahnestock, M., (2004), "Large fluctuations in speed on Greenland's Jakobshavn Isbrae Glacier", *Nature* 432: 608-610

Joughin, I., Howat, I., Alley, R.B., Ekstrom, G., Fahnestock, M., Moon, T., Nettles, M., Truffer, M. and Tsai, V.C., (2008), "Ice-front variation and tidewater behavior on Helheim and Kangerdlugssuaq Glaciers, Greenland", *Journal of Geophysical Research-Earth Surface* 113(F1)

Joughin, I., Smith, B.E., Howat, I.M., Scambos, T, Moon, T., (2010), "Greenland flow variability from ice-sheet-wide velocity mapping", *Journal of glaciology* 56(197): 415-430

Kargel, J.S., Abrams, M.J., Bishop, MP., Bush, A., Hamilton, G., Jiskoot, H., Kaab, A., Kieffer, H.H., Lee, E.M., Paul, F., Rau, F., Raup, B., Shroder, J.F., Soltesz, D., Stainforth, D., Stearns, L. And Wessels, R., (2005), "Multispectral imaging contributions to global land ice measurements from space", *Remote sensing of environment* 99(1-2): 187-219

Kelly, M. A. and Lowell, T.V., (2009), "Fluctuations of local glaciers in Greenland during latest Pleistocene and Holocene time", *Quaternary Science Reviews* 28(21-22): 2088-2106

Khan, S.A., Wahr, J., Bevis, M., Velicogna, I. and Kendrick, E., (2010), “Spread of ice mass loss into northwest Greenland observed by GRACE and GPS”, *Geophysical research letters* 37: LO6501

Koch, L., (1928), "Contributions to glaciology of north Greenland", *Meddelelser om Gronland* 65: 181-464

Koch, L., (1940), “Survey of North Greenland”, Meddelelser om Gronland 130(1)

Koch, L., (1945), “The East Greenland ice”, *Meddelelser om Gronland* 130(3)

Kollmeyer, R.C., (1980), “West Greenland outlet glaciers: an inventory of the major iceberg producers”, *IAHS-AISH publication 126*

Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W. and Yungel, J., (2000), “Greenland ice shet: high-elevatin balance and peripheral thinning”, *Science* 289(5478): 428-430

Li, Z., Sun, W. and Zeng, Q., (1998), “Measurements of glacier variation in the Tibetan Plateau using Landsat data”, *Remote Sensing of Environment* 63: 258-264

Loewe, F., (1966), “The temperature of the Sukkertoppen ice cap”, *Journal of glaciology* 6: 179

Mather, P.M., (1999), *Computer Processing of Remotely-Sensed Images, an Introduction*, John Wiley & Sons, United Kingdom

Meier, M.F., (1984), “Contribution of small glaciers to global sea level”, *Science* 226(4681): 1418-1421

Meier, M.F. and Post, A., (1987), “Fast tidewater glaciers”, *Journal of geophysical research* 92: 9051-9058

Mock, S.J., (1966), “Fluctuations of the terminus of the Harald Moltke Bræ Greenland”, *Journal of glaciology* 6(45): 369-373.

Moon, T. and Joughin, I., (2008), "Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007", *Journal of Geophysical Research* 113: F02022

NASA (2010), "The Landsat program". Available online at: http://landsat.gsfc.nasa.gov/ [last accessed 02/0/10]

Nick, F. M., Vieli, A., Howat, I.M. and Joughin, I., (2009), "Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus", *Nature Geoscience* 2(2): 110-114

Nye, J.F., (1960), "The response of glaciers and ice sheets to seasonal and climatic changes", *Proceedings of the Royal Society of London, series A* 256:559-584

Oerlemans, J., (2005), "Extracting a climate signal from 169 glacier records", *Science* 308: 675-677

Ohmura, A., (2006), "Changes in mountain glaciers and ice caps during the 20th century", *Annals of glaciology* 43(1): 361-368

Ohmura, A. and Reeh, N., (1991), "New precipitation and accumulation maps for Greenland", *Journal of Glaciology* 37: 140-148

Owen, L.A., Thackray, G., Anderson, R.S., Briner, J., Kaufman, D., Roe, G., Pfeffer, W. And Li, C., (2009), "Integrated research on mountain glaciers: current status, priorities and future prospects", *Geomorphology* 103: 158-171

Parizek, B.R. and Alley, R.B., (2004), "Implications of increased Greenland surface melt under global warming scenarios: ice sheet simulations", *Quaternary science reviews* 23: 1013-1027

Paterson, W.S.B., (1994), *The physics of glaciers, 3rd edition*, Oxford, Pergamon Press

Paterson, W.S.B. and Reeh, N., (2001), "Thinning of the ice sheet in northwest Greenland over the past forty years", *Nature* 414: 60-62

Paul, F.,(2002) "Changes in glacier area in Tyrol, Austria, between 1969 and 1992 derived from Landsat 5 Thematic Mapper and Austrian Glacier Inventory data", *International Journal of Remote Sensing*, 23(4): 787 - 799

Paul, F., Kaab, A., Maisch, M., Kellenberger, T. and Haeberli, W., (2002), "The new remote-sensing-derived Swiss glacier inventory: methods", *Annals of glaciology* 34: 355-361

Paul, F. and Andreassen, L.M., (2009), "A new glacier inventory for the Svartisen region, Norway, from Landsat ETM+ data: challenges and change assessment", *Journal of glaciology* 55(192): 607-618

Peary, R. E., (1898), *Northward over the Great Ice*, New York: Frederick A. Stokes

Price, S., (2009), "From the front", *Nature geoscience* 2: 93-94

Pritchard, H. D., Arthern, R.J., Vaughan, D.G. and Edwards, L.A., (2009), "Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets," *Nature*: 1-4

Raper, S. C. B. and Braithwaite, R. J., "Glacier volume response time and its links to climate and topography based on a conceptual model of glacier hypsometry", *The Cryosphere* 3 (2009): 183-194

Rasmussen, K., (1928), "Report of the II Thule Expedition for the exploration of Greenland from Melville Bay to De Long Fjord, 1916-1918", *Meddelelser om Gronland* 65(1), 180 pp.
Rau, F., Mauz, F., De Angelis, H., Jana, R., Arigony Neto, J., Skvarca, P., *et al.,* (2004), "Variations of glacier frontal positions on the Northern Antarctic Peninsula", *Annals of glaciology* 39: 525

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C. and Kaplan, A., (2003), "Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century", *Journal of geophysical research* 108 (D14): 4407

Ribergaard, M.H., Olsen, S.M. and Mortensen, J., (2008), "Oceanographic investigations off West Greenland, 2007", *NAFO scientific council documents 07/003*

Rignot, E., Gogineni, S., Joughin, I. And Krabill, W., (2001), "Contribution to the glaciology of northern Greenland from satellite radar interferometry", *Journal of geophysical research* 106(D24): 34007 - 34019

Rignot, E. and Kanagaratnam, P., (2006), "Changes in the velocity structure of the Greenland ice sheet", *Science* 311(5763): 986-990

Rink, H., (1853), "On the large continental ice of Greenland, and the origin of icebergs in the Arctic seas", *Journal of the Royal Geographical Society of London* 23: 145-154

Sidjak, R. W. and Wheate, R.D., (1999) "Glacier mapping of the Illecillewaet icefield, British Columbia, Canada, using Landsat TM and digital elevation data", *International Journal of Remote Sensing*, 20 (2): 273 - 284

Silverio, W. and Jaquet, J-M., (2005), "Glacial cover mapping (1987-1996) of the Cordillera Blanca (Peru) using satellite imagery", *Remote sensing of environment* 95: 342-350

Sohn, H. G., Jezek, K.C., and Van der Veen, C.J., (1998), "Jakobshavn Glacier, West Greenland: 30 years of spaceborne observations", *Geophysical Research Letters* 25(14): 2699-2702

Sohn, H-G. and Kim, K-T., (2000), "Horizontal positional accuracy assessment of historical ARGON satellite photography", *Journal of civil engineering* 4(1): 59-65

Sole, A., Payne, T., Bamber, J., Nienow, P. and Krabill, W., (2008), "Testing hypotheses of the cause of peripheral thinning of the Greenland Ice Sheet: is land-terminating ice thinning at anomalously high rates?", *The cryosphere* 2: 673-710

Stearns, L.A., Hamilton, G.S and Reeh, N., (2005), "Multi-decadal record of ice dynamics on Daugaard Jensen Gletscher, East Greenland, from satellite imagery and terrestrial measurements", *Annals of glaciology* 42: 53-58

Stearns, L.A. and Hamilton, G.S., (2006), "Dynamics of large tidewater glaciers in East Greenland". In: The Mass Budget of Arctic Glaciers. Extended abstracts.Workshop and GLACIODYN Planning Meeting, 29th January – 3rd February 2006, Obergurgl (Austria), IASC Working Group on Arctic Glaciology, IMAU, Utrecht, 102-104.

Stokes, C.R., Gurney, S.D., Shahgedanova, M. and Popovnin, V., (2006), "Late-20th-century changes in glacier extent in the Caucasus Mountains, Russia/ Georgia", *Journal of glaciology* 52(176): 99-109

Sugden, J. C. and Mott, P.G., (1938), "Oxford University Greenland expedition, 1938", *The geographical journal* 95(1): 43-51

Thomas, R., Frederick, E., Krabill, W., Manizade, S. and Martin, C., (2009), "Recent changes on Greenland outlet glaciers", *Journal of glaciology* 55 (189): 147-162

Tsutomo, K. and Gombo, D., (2007), “Recent glacier variations in Mongolia”, *Annals of glaciology* 46: 185-188

Van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., Van de Berg, W.J., van Meijgaard, E., Velicogna, I. and Wouters, B., (2009), “Partitioning recent Greenland mass loss”, *Science* 326(984): 984-986

Van Ede, R., (2004), “Destriping and geometric correction of an ASTER level 1a image”. Available online at: http://gis-lab.info/docs/aster-report-v3.pdf

Velicogna, I. (2009), “Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE”, *Geophysical research letters* 36: L19503

Wake, L.M., Huybrechts, P., Box, J.E., Hanna, E., Janssens, I. And Milne, G.A., (2009), “Surface mass balance changes of the Greenland ice sheet since 1866”, *Annals of glaciology* 50(50): 178-184

Warren, C. R., (1991), "Terminal environment, topographic control and fluctuations of west Greenland glaciers”, *Boreas* 20(1): 1-15

Warren, C. R. and Glasser, N.F., (1992), "Contrasting response of south Greenland glaciers to recent climatic change”, *Arctic and Alpine Research* 24(2): 124-132

Weidick, A., (1959), "Glacial variations in West Greenland in historical time", *Meddelelser om Gronland* 158(4)

Weidick, A., (1963), “Ice margin features in the Julianshåb district, South Greenland”, *Meddelelser om Gronland* 165(3), 133 pp.

Weidick, A., (1968), “Observations on Some Holocene Glacier Fluctuations in West Greenland”, *Meddelelser om Gronland* 164(6): 202 pp.

Weidick, A., (1984), “Studies of glacier behaviour and glacier mass balance in Greenland: a review”, *Geografiska Annaler, series A: physical geography* 66(3): 183-195

Weidick, A., (1994), "Historical fluctuations of calving glaciers in South and West Greenland", *Rapport Grønlands Geologiske Undersøgelse* 161: 73-79

Weidick, A., (1995), *Satellite Image Atlas of Glaciers of the World, Greenland,* USGS Professional Paper 1386-C, United States Government Printing Office, Washington

Weidick, A., (2009), “Johan Dahl Land, south Greenland: the end of a 20th century glacier expansion”, *Polar record* 45: 337-350

Weidick, A., Boggild, C.E., Knudsen, N.T., (1992), "Glacier inventory and atlas of west Greenland", *Rapport Grønlands Geologiske Undersøgelse* 158

Weidick, A. and Morris, E., (1998), "Local glaciers surrounding the continental ice sheets", In: Haeberli, W., Hoelzle, M. and Suter, S. (eds.), “Into the second century of worldwide glacier monitoring: prospects and strategies”, *Studies and reports in hydrology*. Paris: UNESCO publishing, 197-208

WGMS, (2008a), *Global glacier changes: facts and figures,* Zurich, Switzerland

WGMS, (2008b), *Fluctuations of Glaciers 2000–2005, Volume IX,* Zurich, Switzerland

Wright, J.W., (1939), “Contributions to the glaciology of Northwest Greenland”, *Meddelelser om Gronland* 125(3)

Wu, X., Heflin, M.B., Schotman, H., Vermeersen, B.L.A., Dong, D., Gross, R.S., Ivins, E.R., Moore, A.W. and Owen, S.E., (2010), “Simultaneous estimation of global present day water transport and glacial isostatic adjustment”, *Nature geoscience* 3: 642-646

Yde, J. C. and Knudsen, N.T., (2006), “20th-century glacier fluctuations on Disko Island (Qeqertarsuaq), Greenland”, *Annals of Glaciology* 46: 209-214

Zemp, M., Hoelzle, M. and Haeberli, W., (2009), “Six decades of glacier mass balance observation: a review of the worldwide monitoring network”, *Annals of glaciology* 50 (50): 101-111

Zhou, G., Jezek, K., Wright, W., Rand, J. and Granger, J., (2002), “Orthorectification of 1960s satellite photographs covering Greenland”, *IEEE transactions on geoscience and remote sensing* 40(6): 1247-1259

Zwally, H.J., Bindschadler, R.A., Brenner, A.C., Major, J.A. and Marsh, J.G., (1989), “Growth of Greenland Ice Sheet: measurement”, *Science* 246 (4937): 1587-1589

Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J. and Steffen, K., (2002), “Surface melt induced acceleration of Greenland Ice Sheet flow”, *Science* 297(5579): 218-222

Appendix A: study area maps

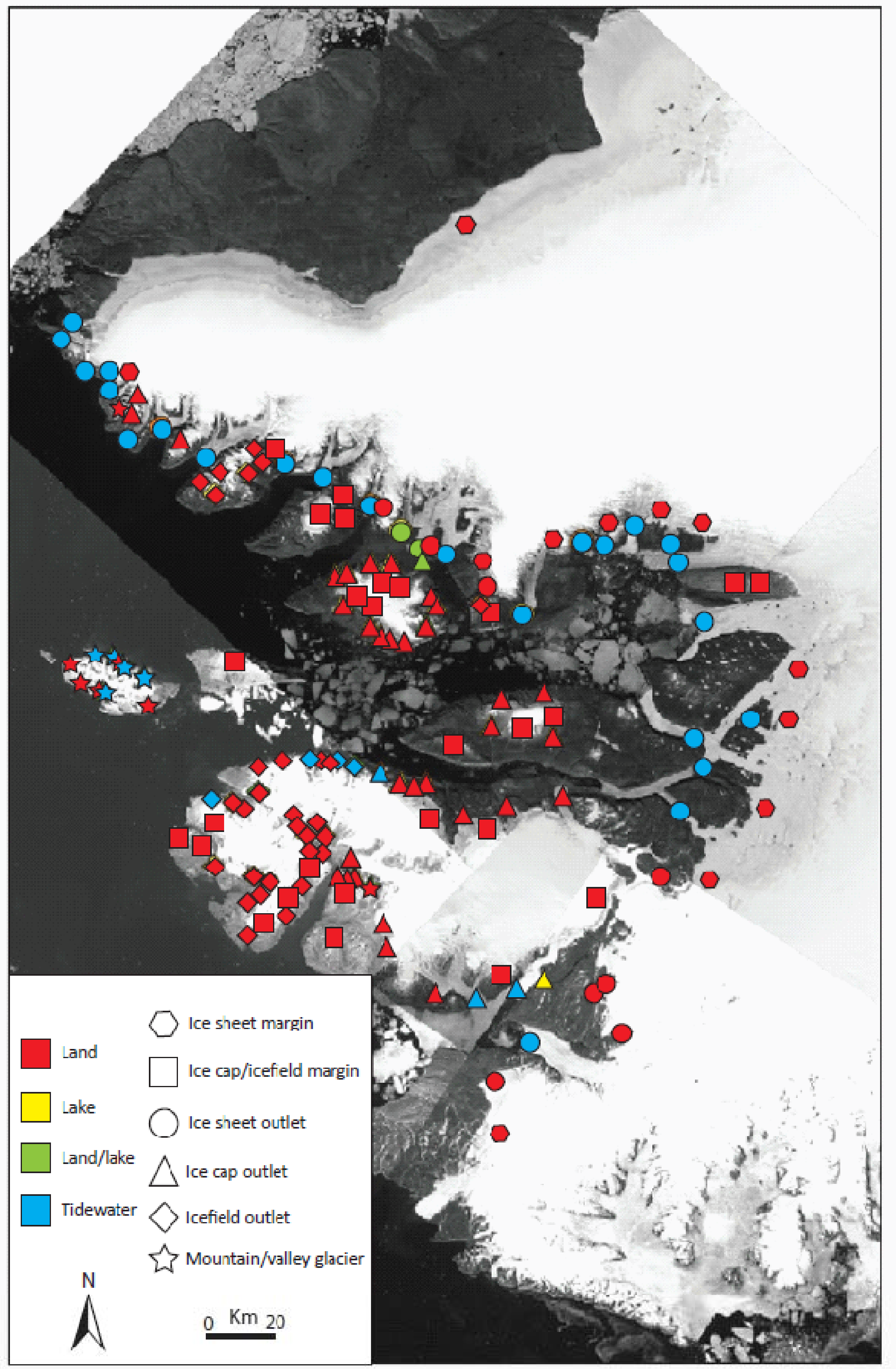


Figure A1: Map of the northwest study area showing the locations of all glaciers mapped. The shapes indicate glacier class and the colours terminus environment. Background is the 1999 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

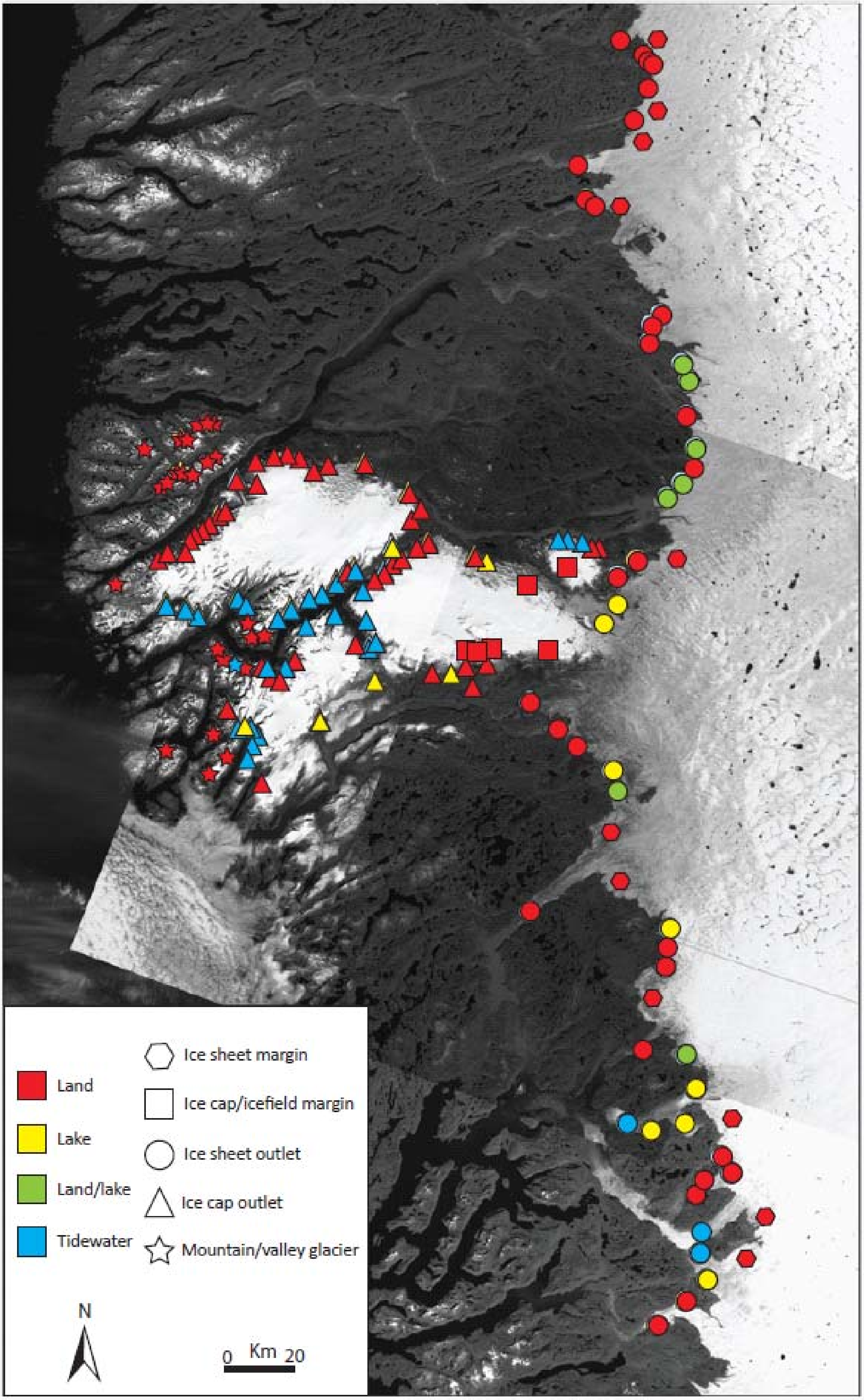


Figure A2: Map of the southwest study area showing the locations of all glaciers mapped. The shapes indicate glacier class and the colours terminus environment. Background is the 2001 Landsat base image, displayed using bands 4,3,2 (red, green, blue).

Appendix B: glacier data file

Glacier ID	Number of years of data	Earliest year	Most recent year	Range (years)	Original length (km)	Total length change (% of original)	Rate of change (% per year)	Aspect	Primary classification	Terminus environment
1	3	1999	2007	8	32.7	-0.47	-0.06	NW	Ice sheet outlet	Tidewater
2	3	1999	2007	8	31.3	0.64	0.08	W	Ice sheet outlet	Land
3	4	1999	2009	10	6.3	3.75	0.38	S	Ice sheet outlet	Tidewater
4	4	1999	2009	10	13.9	-1.24	-0.12	S	Ice sheet outlet	Tidewater
5	4	1999	2009	10	21.6	0.77	0.08	W	Ice sheet outlet	Tidewater
6	4	1999	2009	10	2.1	0.61	0.06	NW	Mountain/valley	Land
7	3	1999	2009	10	3.4	0.41	0.04	NW	Ice cap outlet	Land
8	3	1999	2007	8	6.1	5.44	0.68	SW	Ice cap outlet	Land
9	5	1964	2009	45	31.8	0.71	0.02	SW	Ice sheet outlet	Tidewater
10	6	1890	2009	119	26.5	-9.01	-0.08	S	Ice sheet outlet	Tidewater
11	4	1890	2007	117	7.1	-9.24	-0.08	W	Ice sheet outlet	Land
12	5	1890	2009	119	4.3	-22.61	-0.19	SE	Ice sheet outlet	Land
13	5	1964	2009	45	35.4	1.88	0.04	SW	Ice sheet outlet	Tidewater
14	4	1890	2007	117	7.6	-4.10	-0.04	NW	Icefield outlet	Land
15	5	1890	2009	119	5.8	-6.22	-0.05	NW	Icefield outlet	Land
16	6	1890	2009	119	8.9	-3.24	-0.03	SW	Icefield outlet	Land
17	5	1890	2007	117	9.9	-7.92	-0.07	SE	Icefield outlet	Land
18	4	1890	2007	117	5.0	-9.44	-0.08	S	Icefield outlet	Land
19	5	1890	2009	119	3.4	-18.19	-0.15	N	Icefield outlet	Land
20	6	1890	2009	119	14.7	-5.30	-0.04	S	Ice sheet outlet	Tidewater
21	6	1964	2009	45	42.2	-0.10	0.00	S	Ice sheet outlet	Tidewater
22	7	1890	2009	119	37.4	-3.99	-0.03	S	Ice sheet outlet	Tidewater
23	4	1999	2009	10	5.4	2.38	0.24	W	Ice sheet outlet	Land
24	7	1890	2009	119	37.9	-2.33	-0.02	S	Ice sheet outlet	Land/ lake
25	1	1999	1999	0	37.1	-	-	S	Ice sheet outlet	Land
26	6	1975	2009	34	49.4	0.08	0.00	S	Ice sheet outlet	Land/lake
27	6	1890	2009	119	52.8	-0.20	0.00	S	Ice sheet outlet	Land
28	6	1975	2009	34	46.4	0.32	0.01	S	Ice sheet outlet	Tidewater
29	7	1890	2009	119	16.3	-0.68	-0.01	N	Ice cap outlet	Land/lake
30	5	1975	2009	34	4.9	-5.09	-0.15	E	Ice cap outlet	Land
31	7	1890	2009	119	12.1	-1.41	-0.01	E	Ice cap outlet	Land
32	8	1890	2009	119	9.6	-3.44	-0.03	SE	Ice cap outlet	Land
33	8	1890	2009	119	6.9	-19.08	-0.16	SW	Ice cap outlet	Land
34	7	1890	2009	119	3.6	-11.77	-0.10	SW	Ice cap outlet	Land
35	7	1890	2009	119	5.8	-7.62	-0.06	SW	Ice cap outlet	Land
36	8	1890	2009	119	7.2	-14.16	-0.12	SW	Ice cap outlet	Land
37	7	1890	2009	119	13.3	-3.82	-0.03	SW	Ice cap outlet	Land
38	6	1890	2009	119	3.6	-15.84	-0.13	NW	Ice cap outlet	Land
39	5	1890	2009	119	3.9	-15.62	-0.13	NW	Ice cap outlet	Land
40	6	1890	2009	119	7.4	-8.62	-0.07	NW	Ice cap outlet	Land
41	7	1890	2009	119	4.2	-12.52	-0.11	N	Ice cap outlet	Land
42	6	1890	2009	119	9.8	-3.21	-0.03	SW	Ice sheet outlet	Land
43	7	1890	2009	119	6.6	-18.35	-0.15	W	Icefield outlet	Land
44	8	1890	2009	119	72.1	-3.54	-0.03	S	Ice sheet outlet	Tidewater
45	8	1890	2009	119	58.7	-22.22	-0.19	SE	Ice sheet outlet	Tidewater
46	8	1890	2009	119	59.1	-8.51	-0.07	S	Ice sheet outlet	Tidewater
47	8	1964	2009	45	56.6	8.23	0.18	S	Ice sheet outlet	Tidewater
48	8	1964	2009	45	63.8	-35.35	-0.79	S	Ice sheet outlet	Tidewater
49	7	1964	2007	43	77.9	-15.81	-0.37	W	Ice sheet outlet	Tidewater
50	7	1972	2009	37	78.4	4.16	0.11	W	Ice sheet outlet	Tidewater
51	8	1975	2009	34	76.5	0.06	0.00	W	Ice sheet outlet	Tidewater
52	8	1964	2007	43	70.7	0.15	0.00	SW	Ice sheet outlet	Tidewater
53	9	1964	2009	45	58.7	2.21	0.05	NW	Ice sheet outlet	Land
54	4	1975	2007	32	68.3	0.84	0.03	NW	Ice sheet outlet	Tidewater
55	7	1964	2007	43	10.3	0.61	0.01	N	Ice sheet outlet	Land
56	6	1972	2009	37	17.6	0.73	0.02	W	Ice sheet outlet	Land
57	6	1953	2009	56	21.0	1.04	0.02	W	Ice sheet outlet	Land
58	4	1995	2009	14	4.9	-1.10	-0.08	S	Ice sheet outlet	Land
59	8	1890	2009	119	84.8	-24.02	-0.20	W	Ice sheet outlet	Tidewater
60	5	1953	2007	54	15.7	0.43	0.01	SW	Ice sheet outlet	Land
61	8	1890	2009	119	10.6	-6.69	-0.06	SW	Ice cap outlet	Land
62	9	1890	2007	117	10.7	-7.71	-0.07	SE	Ice cap outlet	Land
63	4	1995	2007	12	7.2	0.74	0.06	N	Ice cap outlet	Land
64	7	1975	2009	34	7.9	-1.50	-0.04	N	Ice cap outlet	Land
65	7	1964	2009	45	30.9	-0.33	-0.01	SW	Ice cap outlet	Lake
66	8	1953	2009	56	33.8	1.18	0.02	SW	Ice cap outlet	Tidewater
67	7	1953	2009	56	34.7	-0.83	-0.01	SE	Ice cap outlet	Tidewater
68	7	1953	2009	56	24.3	-0.45	-0.01	SW	Ice cap outlet	Land
69	5	1890	2009	119	9.6	0.09	0.00	SW	Ice cap outlet	Land
70	4	1890	2009	119	11.2	-2.48	-0.02	SW	Ice cap outlet	Land
71	5	1890	2009	119	3.0	-16.78	-0.14	N	Mountain/valley	Land
72	3	1964	2007	43	4.3	-13.07	-0.30	N	Ice cap outlet	Land
73	6	1890	2009	119	4.0	-18.84	-0.16	N	Ice cap outlet	Land
74	4	1964	2009	45	3.6	-2.22	-0.05	NW	Ice cap outlet	Land
75	6	1953	2009	56	38.4	-5.68	-0.10	W	Ice cap outlet	Land/tidewater*
76	3	1995	2002	7	15.8	0.51	0.07	NW	Ice cap outlet	Land
77	7	1964	2009	45	14.0	-0.46	-0.01	NW	Ice cap outlet	Land
78	8	1953	2007	54	25.8	0.49	0.01	N	Ice cap outlet	Land
79	7	1890	2009	119	13.4	-10.42	-0.09	N	Ice cap outlet	Land
80	5	1890	2009	119	10.6	-1.67	-0.01	N	Ice cap outlet	Land
81	7	1890	2009	119	8.8	-7.08	-0.06	N	Ice cap outlet	Land
82	7	1890	2009	119	11.2	-8.25	-0.07	N	Ice cap outlet	Tidewater
83	4	1999	2009	10	11.3	0.79	0.08	N	Ice cap outlet	Tidewater
84	7	1890	2009	119	7.5	-4.76	-0.04	N	Icefield outlet	Tidewater
85	5	1890	2009	119	3.9	-17.20	-0.14	N	Icefield outlet	Land
86	5	1890	2009	119	4.2	-14.82	-0.12	N	Icefield outlet	Land
87	4	1987	2009	22	9.9	-1.06	-0.05	N	Icefield outlet	Tidewater
88	3	1890	2007	117	3.2	-23.76	-0.20	NW	Icefield outlet	Land
89	4	1987	2009	22	4.2	-8.64	-0.39	NW	Icefield outlet	Land
90	6	1890	2009	119	16.1	-1.65	-0.01	W	Icefield outlet	Land
91	3	1999	2009	10	7.2	-2.17	-0.22	N	Icefield outlet	Land
92	6	1890	2009	119	11.7	-5.17	-0.04	N	Icefield outlet	Land
93	4	1964	2009	45	5.3	-6.94	-0.15	NW	Icefield outlet	Land

94	6	1890	2009	119	16.6	-6.12	-0.05	SW	Icefield outlet	Land
95	5	1890	2007	117	11.5	-11.91	-0.10	S	Icefield outlet	Land
96	6	1890	2009	119	9.1	-2.58	-0.02	SW	Icefield outlet	Land
97	4	1890	2009	119	8.7	-23.78	-0.20	W	Icefield outlet	Land
98	3	1999	2009	10	3.0	-10.20	-1.02	W	Icefield outlet	Land
99	5	1890	2009	119	11.7	-4.13	-0.03	S	Icefield outlet	Land
100	4	1890	2009	119	8.5	-8.89	-0.07	SE	Icefield outlet	Land
101	5	1890	2009	119	5.6	-6.07	-0.05	E	Icefield outlet	Land
102	4	1987	2009	22	5.5	-8.26	-0.38	N	Icefield outlet	Land
103	6	1890	2009	119	19.3	-4.16	-0.03	S	Icefield outlet	Land
104	6	1890	2009	119	16.4	-2.67	-0.02	E	Icefield outlet	Land
105	3	1999	2009	10	3.5	-3.31	-0.33	N	Icefield outlet	Land
106	4	1890	2009	119	7.3	-8.25	-0.07	S	Icefield outlet	Land
107	4	1987	2009	22	12.5	0.24	0.01	S	Icefield outlet	Land
108	4	1987	2009	22	10.8	-1.57	-0.07	S	Icefield outlet	Lake
109	4	1890	2009	119	6.7	-7.95	-0.07	N	Mountain/valley	Tidewater
110	5	1890	2009	119	7.8	-3.16	-0.03	N	Mountain/valley	Tidewater
111	4	1890	2009	119	5.8	-5.71	-0.05	N	Mountain/valley	Tidewater
112	5	1890	2009	119	7.0	-8.10	-0.07	N	Mountain/valley	Tidewater
113	6	1890	2009	119	6.4	-6.82	-0.06	NE	Mountain/valley	Tidewater
114	4	1964	2009	45	7.5	1.21	0.03	E	Mountain/valley	Land
115	4	1890	2009	119	9.0	-11.66	-0.10	SW	Mountain/valley	Tidewater
116	5	1890	2009	119	5.2	-4.95	-0.04	S	Mountain/valley	Land
117	4	1890	2009	119	4.4	-14.92	-0.13	S	Mountain/valley	Land
118	4	1890	2009	119	4.0	-12.82	-0.11	W	Mountain/valley	Land

Table B1: Summary statistics and characteristics of all ice sheet outlets, ice cap outlets, icefield outlets and mountain/valley glaciers mapped in the northwest study area.

Glacier ID	Number of years of data	Earliest year	Most recent year	Range (years)	Original length (km)	Margin width (km)	Total length change (% of original)	Rate of change (% per year)	Aspect	Primary classification	Terminus environment
IS001	5	1964	2009	45	35.3	176.9	0.00	0.00	NW	Ice sheet margin	Land
IS002	8	1999	2009	10	15.9	8.6	0.00	0.00	S	Ice sheet margin	Land
IS003	8	1975	2009	34	10.9	35.0	-0.02	0.00	SW	Ice sheet margin	Land
IS004	6	1975	2009	34	16.4	16.1	0.00	0.00	S	Ice sheet margin	Land
IS005	6	1975	2009	34	2.4	25.7	-0.07	0.00	S	Ice sheet margin	Land
IS006	3	1975	2007	32	50.0	11.9	0.00	0.00	S	Ice sheet margin	Land
IS007	4	1975	2009	34	50.0	13.2	0.00	0.00	S	Ice sheet margin	Land
IS008	3	1964	2009	45	50.0	13.2	-0.01	0.00	W	Ice sheet margin	Land
IS009	3	1964	2009	45	50.0	10.8	0.00	0.00	W	Ice sheet margin	Land
IS010	3	1964	2007	43	50.0	23.6	0.00	0.00	W	Ice sheet margin	Land
IS011	3	1975	2007	32	50.0	22.4	0.00	0.00	NW	Ice sheet margin	Land
IS012	3	1987	2007	20	14.9	45.9	-0.01	0.00	W	Ice cap/icefield margin	Land
NI001	6	1972	2009	37	12.3	24.6	0.00	0.00	E	Ice cap/icefield margin	Land
NI002	6	1972	2009	37	4.5	15.1	-0.02	0.00	SE	Ice cap/icefield margin	Land
NI003	3	1999	2009	10	2.0	26.2	-0.08	-0.01	SE	Ice cap/icefield margin	Land
NI004	3	1999	2009	10	2.7	5.9	-0.09	-0.01	E	Ice cap/icefield margin	Land
NI005	3	1999	2009	10	2.2	13.9	-0.08	-0.01	SE	Ice cap/icefield margin	Land
NI006	4	1890	2009	119	2.6	27.6	0.06	0.00	W	Ice cap/icefield margin	Land
NI007	6	1964	2007	43	5.3	15.3	-0.10	0.00	NE	Ice cap/icefield margin	Land
NI008	6	1964	2007	43	9.3	33.9	-0.03	0.00	N	Ice cap/icefield margin	Land
OI001	2	1999	2007	8	0.9	6.8	-0.03	0.00	All	Ice cap/icefield margin	Land
OI002	3	1999	2009	10	4.4	50.1	-0.16	-0.02	All	Ice cap/icefield margin	Land
OI003	3	1999	2009	10	1.0	9.4	-0.08	-0.01	All	Ice cap/icefield margin	Land
OI004	2	1999	2007	8	0.5	3.8	-0.06	-0.01	All	Ice cap/icefield margin	Land
OI005	6	1890	2007	117	4.7	9.6	0.03	0.00	S	Ice cap/icefield margin	Land
OI006	4	1890	2007	117	3.7	12.8	0.07	0.00	SW	Ice cap/icefield margin	Land
OI007	4	1999	2009	10	4.0	4.9	-0.01	0.00	N	Ice cap/icefield margin	Land
OI008	5	1975	2009	34	4.4	5.7	-0.07	0.00	NE	Ice cap/icefield margin	Land
OI009	7	1890	2009	119	2.7	21.3	0.09	0.00	All	Ice cap/icefield margin	Land
OI010	8	1964	2009	45	2.1	15.1	-0.20	0.00	All	Ice cap/icefield margin	Land
OI011	8	1964	2009	45	2.0	8.3	-31.12	-0.69	All	Ice cap/icefield margin	Land
OI012	6	1890	2007	117	4.5	11.3	0.25	0.00	SE	Ice cap/icefield margin	Land
OI013	6	1890	2007	117	4.2	11.2	0.18	0.00	S	Ice cap/icefield margin	Land
OI014	3	1999	2007	8	2.1	27.6	0.18	0.02	All	Ice cap/icefield margin	Land
OI015	4	1999	2009	10	2.0	51.8	-3.11	-0.31	All	Ice cap/icefield margin	Land
OI016	3	1999	2009	10	0.9	10.7	-0.34	-0.03	All	Ice cap/icefield margin	Land
OI017	3	1999	2009	10	1.3	16.4	-0.09	-0.01	All	Ice cap/icefield margin	Land
OI018	3	1999	2009	10	1.3	15.1	-0.28	-0.03	All	Ice cap/icefield margin	Land
OI019	3	1999	2009	10	2.0	13.4	-0.08	-0.01	S	Ice cap/icefield margin	Land

Table B2: Summary statistics and characteristics of all ice sheet margins and ice cap/icefield margins mapped in the northwest study area.

Glacier ID	Number of years of data	Earliest year	Most recent year	Range (years)	Original length (m)	Total length change (% of original)	Rate of change (% per year)	Latitude	Longitude	Aspect	Highest elevation (m)	Terminus elevation (m)	Area (km^2)	Primary classification	Terminus environment
1CG 13 003	4	1964	2009	45	51.7	-16.91	-0.38	64 11	49 42	NW	1800	450	74.0	Ice sheet outlet	Land
1CG 14 001	5	1890	2009	119	96.1	-7.30	-0.06	64 10	49 46	NW	1800	200		Ice sheet outlet	Land
1CH 02 001	5	1964	2009	45	77.7	3.50	0.08	65 15	50 33	SW	1800	100	2047.8	Ice sheet outlet	Land
1CH 02 014	4	1964	2009	45	54.1	11.21	0.25	65 09	49 42	W	1800	800	292.4	Ice sheet outlet	Lake
1CH 02 015	4	1987	2009	22	52.8	10.68	0.49	65 07	49 44	W	1800	850	132.8	Ice sheet outlet	Land
1CH 02 016	5	1964	2009	45	50.8	33.82	0.75	65 02	49 50	W	1800	750	526.4	Ice sheet outlet	Land
1CH 13 002	4	1890	2007	117	96.1	-0.86	-0.01	64 53	49 53	SW	1800	50	456.5	Ice sheet outlet	Land
1CH 13 004	6	1890	2009	119	96.1	-0.24	0.00	64 50	49 39	W	1800	750	361.5	Ice sheet outlet	Land/lake
1CH 17 002a	4	1964	2009	45	51.6	-3.39	-0.08	64 41	49 48	W	1800			Ice sheet outlet	Lake
1CH 17 002b	3	1987	2009	22	55.5	-7.38	-0.34	64 41	49 48	W	1800			Ice sheet outlet	Lake
1CH 17 002c	5	1890	2009	119	55.0	-67.30	-0.57	64 41	49 48	W	1800			Ice sheet outlet	Lake
1CH 17 002d	3	1964	2001	37	81.2	0.67	0.02	64 41	49 48	W	1800		1188.0	Ice sheet outlet	Tidewater
1CH 21 001	5	1890	2009	119	96.1	-2.90	-0.02	64 34	49 27	SW	1800	400	169.2	Ice sheet outlet	Land
1CH 21 002	5	1890	2009	119	52.7	-24.53	-0.21	64 29	49 32	SW	1800	600		Ice sheet outlet	Land
1CH 21 002	5	1890	2009	119	51.8	-63.62	-0.53	64 29	49 32	SW	1800	600		Ice sheet outlet	Land
1CH 21 002	5	1890	2009	119	67.7	-3.42	-0.03	64 29	49 32	SW	1800	600	327.2	Ice sheet outlet	Land
1CH 22 001	3	1890	2001	111	78.3	-32.20	-0.29	64 22	49 37	SW	1800		338.3	Ice sheet outlet	Tidewater
1CH 23 003a	5	1890	2009	119	82.0	-37.87	-0.32	64 15	49 32	W	1800			Ice sheet outlet	Tidewater
1CH 23 003b	5	1890	2009	119	72.3	-20.86	-0.18	64 15	49 32	W	1800		1551.5	Ice sheet outlet	Lake
1DB 03 001	4	1890	2009	119	6.7	-9.01	-0.08	65 32	52 20	W	1000	200	14.0	Ice cap outlet	Land
1DB 10 009	5	1964	2009	45	22.3	-7.49	-0.17	65 43	52 00	SE	1000	100	58.6	Ice cap outlet	Lake
1DB 10 016	4	1890	2009	119	33.1	-2.91	-0.02	65 41	51 37	SW	1900	350	40.3	Ice cap outlet	Lake
1DB 11 009	5	1890	2009	119	12.1	-10.43	-0.09	65 54	51 11	S	1900	400	35.9	Ice cap outlet	Land
1DB 11 010	5	1890	2009	119	11.3	-13.07	-0.11	65 51	51 06	S	1900	50	57.6	Ice cap outlet	Lake
1DB 11 011	5	1890	2009	119	8.1	-7.48	-0.06	65 52	51 04	S	1530	650	16.9	Ice cap outlet	Land
1DB 11 012	5	1890	2009	119	2.8	-3.53	-0.03	65 52	51 01	S	1530	900	6.0	Ice cap outlet	Land
1DB 11 013	5	1890	2009	119	44.6	-3.05	-0.03	65 54	50 57	SW	2000	500	185.1	Ice cap outlet	Land
1DB 11 021	4	1964	2007	43	72.2	1.93	0.04	65 47	50 25	W	1800	100	1413.4	Ice sheet outlet	Land
1DB 11 022	3	1987	2007	20	59.5	4.65	0.23	65 43	50 12	W	1800	100	284.1	Ice sheet outlet	Land
1DB 11 023	3	1987	2007	20	54.8	-0.26	-0.01	65 41	50 11	W	1800	400	158.6	Ice sheet outlet	Land
1DB 13 007	5	1964	2009	45	52.7	34.30	0.76	65 36	49 59	W	1800	500	941.9	Ice sheet outlet	Lake
1DB 13 008	4	1987	2009	22	60.0	4.40	0.20	65 32	49 58	W	1800	500	798.2	Ice sheet outlet	Land/lake
1DC 02 004	5	1964	2009	45	16.3	1.14	0.03	65 42	52 28	SW	1350		70.0	Ice cap outlet	Tidewater
1DC 02 005	3	1987	2009	22	18.3	-1.85	-0.08	65 41	52 28	SW	500	100	6.0	Ice cap outlet	Lake
1DC 04 002	4	1890	2001	111	7.6	-5.40	-0.05	65 34	52 41	SW	1000	50	5.3	Mountain/valley	Land
1DC 06 003	3	1890	2001	111	4.8	-18.24	-0.16	65 39	52 30	S	800	600	1.2	Mountain/valley	Land
1DC 07 001	4	1964	2009	45	15.3	-1.77	-0.04	65041	52 27	SW	1200		49.3	Ice cap outlet	Tidewater
1DC 07 002	4	1964	2009	45	7.0	2.06	0.05	65 40	52 23	W	1200		43.7	Ice cap outlet	Tidewater
1DC 07 003	3	1987	2009	22	5.4	0.19	0.01	65 39	52 23	NW	1350		9.2	Ice cap outlet	Tidewater
1DC 07 005	2	1987	2001	14	2.9	-0.26	-0.02	65 37	52 26	NW	1100	100	3.1	Ice cap outlet	Tidewater
1DD 06 003	6	1890	2009	119	4.8	-2.75	-0.02	65 44	52 34	SW	1200	250	2.4	Ice cap outlet	Land
1DD 06 006	5	1890	2009	119	2.2	-18.84	-0.16	65 41	52 39	NW	1200	150	1.7	Mountain/valley	Land
1DD 07 009	3	1964	2001	37	2.9	0.28	0.01	65 37	53 01	NW	600	100	2.4	Mountain/valley	Land
1DF 02 003	4	1964	2009	45	12.9	-2.35	-0.05	66 04	52 57	SW	1100		49.2	Ice cap outlet	Tidewater
1DF 03 004a	5	1890	2009	119	46.1	-5.14	-0.04	66 02	52 48	SW	1740		240.0	Ice cap outlet	Tidewater
1DF 03 004b	4	1964	2009	45	43.0	-0.21	0.00	66 02	52 48	SW	1740		240.0	Ice cap outlet	Tidewater
1DF 10 005	3	1992	2009	17	12.5	-2.91	-0.17	66 03	52 31	SW	1600		315.8	Ice cap outlet	Tidewater
1DF 11 005	3	1992	2009	17	34.4	-2.14	-0.13	66 04	52 27	SW	1600		211.1	Ice cap outlet	Tidewater
1DF 12 001	3	1890	2001	111	4.1	-21.32	-0.19	65 58	52 30	NW	1200	200	4.0	Mountain/valley	Land
1DF 14 001	5	1964	2009	45	5.6	0.37	0.01	65 56	52 25	S	1600	100	8.6	Mountain/valley	Land
1DF 15 002	4	1890	2001	111	4.3	-29.99	-0.27	65 55	52 22	SW	1800	300	5.7	Mountain/valley	Land
1DF 16 003	2	1987	2001	14	6.9	-0.37	-0.03	65 57	52 20	NE	1600		8.6	Mountain/valley	Tidewater
1DF 17 001	5	1964	2009	45	6.6	-2.69	-0.06	66 01	52 12	SE	1950		27.9	Ice cap outlet	Tidewater
1DF 18 003	5	1890	2009	119	3.8	-7.42	-0.06	66 03	52 04	SE	1800	200	2.8	Ice cap outlet	Tidewater
1DF 19 001	5	1890	2009	119	6.6	-4.83	-0.04	66 02	52 00	S	2000		13.7	Ice cap outlet	Tidewater
1DF 19 007	5	1964	2009	45	7.6	-7.29	-0.16	66 05	51 52	S	1970		23.9	Ice cap outlet	Tidewater
1DF 20 001	5	1890	2001	111	3.3	-16.47	-0.15	66 06	51 50	SE	1800	300	5.0	Ice cap outlet	Land
1DF 20 002	6	1964	2009	45	15.6	-3.73	-0.08	66 08	51 45	S	1880		93.9	Ice cap outlet	Tidewater
1DF 20 004	6	1964	2009	45	9.3	0.68	0.02	66 12	51 35	SE	1700	200	38.4	Ice cap outlet	Lake
1DF 20 007	5	1890	2009	119	5.6	-28.48	-0.24	66 14	51 28	E	1600	950	15.1	Ice cap outlet	Land
1DF 20 009	6	1964	2009	45	12.6	-7.05	-0.16	66 09	51 15	N	1950	400	54.3	Ice cap outlet	Land
1DF 20 011	5	1973	2009	36	9.2	-7.99	-0.22	66 08	51 21	N	1950	200	23.3	Ice cap outlet	Land
1DF 20 012	5	1973	2009	36	8.2	-3.27	-0.09	66 08	51 24	N	1950	200	13.9	Ice cap outlet	Land
1DF 20 014	7	1890	2009	119	8.5	-2.33	-0.02	66 07	51 28	NW	1950	100	29.8	Ice cap outlet	Land
1DF 20 016	6	1964	2009	45	8.5	6.27	0.14	66 05	51 32	W	1950	100	40.9	Ice cap outlet	Land
1DF 20 018	5	1973	2009	36	7.5	-0.64	-0.02	66 03	51 36	NW	1900	150	54.3	Ice cap outlet	Land
1DF 20 021	4	1987	2009	22	9.1	-0.19	-0.01	66 02	51 41	NW	1500		21.0	Ice cap outlet	Tidewater
1DF 20 026	2	1987	2001	14	9.9	-0.57	-0.04	66 01	51 39	SW	1370		4.7	Ice cap outlet	Tidewater
1DF 21 001 a	4	1987	2009	22	14.1	0.05	0.00	65 58	51 42	SW	1190	900	2.1	Ice cap outlet	Tidewater
1DF 21 001 b	6	1890	2009	119	34.5	-5.05	-0.04	65 58	51 42	SW	1190	900	2.1	Ice cap outlet	Tidewater
1DF 21 005	4	1890	2009	119	8.4	-10.55	-0.09	65 55	51 49	NE	1200	400	13.7	Ice cap outlet	Land
1DF 22 002	4	1987	2009	22	15.1	-0.27	-0.01	65 54	51 55	N	1540		69.4	Ice cap outlet	Tidewater
1DF 23 004	4	1987	2009	22	5.7	-0.40	-0.02	65 57	52 04	NW	1600		11.4	Ice cap outlet	Tidewater
1DF 25 003	4	1890	2009	119	5.2	-10.62	-0.09	65 51	52 09	NW	1600	200	18.4	Ice cap outlet	Land
1DF 26 002	4	1890	2009	119	5.4	-9.84	-0.08	65 50	51 12	W	1700		5.8	Ice cap outlet	Tidewater
1DF 27 004	4	1987	2009	22	5.0	-6.66	-0.30	65 47	51 14	NW	1350	100	18.2	Ice cap outlet	Land
1DF 28 001	4	1890	2001	111	4.5	-10.26	-0.09	65 49	52 22	NE	1250		7.6	Ice cap outlet	Land
1DF 29 001	4	1890	2001	111	5.8	-2.71	-0.02	65 51	52 21	NE	1300		4.6	Mountain/valley	Tidewater
1DF 29 002	2	1987	2001	14	4.0	-0.38	-0.03	65 51	52 23	NE	1450	100	3.4	Mountain/valley	Tidewater
1DF 30 001	4	1987	2009	22	10.5	-3.36	-0.15	65 47	52 28	N	1100		19.7	Mountain/valley	Land
1DF 31 002	3	1987	2009	22	3.6	-3.23	-0.15	65 51	52 32	NE	1600		5.4	Mountain/valley	Tidewater
1DF 32 002	1	2001	2001	0	3.1	0.00		65 52	52 37	NE		150	4.8	Mountain/valley	Land
1DF 32 005	2	1992	2001	9	3.8	-1.67	-0.19	65 55	52 39	NE	1400	200		Mountain/valley	land
1DG 02 002/ 1DG 03 001	4	1964	2001	37	60.4	0.68	0.02	67 06	50 06	W	1800	250		Ice sheet outlet	Land
1DG 03 002	5	1972	2009	37	59.2	-0.22	-0.01	67 05	50 00	W	1800	300	161.0	Ice sheet outlet	Land
1DG 08 003	6	1964	2009	45	58.4	8.21	0.18	66 47	49 40	W	1800	300	300.3	Ice sheet outlet	Land
1DG 08 004	6	1964	2009	45	64.4	5.38	0.12	66 45	49 45	W	1800	200	200.0	Ice sheet outlet	Land
1DG 08 005	6	1964	2009	45	67.9	3.43	0.08	66 44	49 47	W	1800	200	354.5	Ice sheet outlet	Land
1DG 08 007	6	1964	2009	45	57.7	2.58	0.06	66 39	49 34	W	1800	450	528.8	Ice sheet outlet	Land/lake
1DG 08 008	6	1964	2009	45	58.3	3.83	0.09	66 37	49 32	W	1800	450	207.4	Ice sheet outlet	Land/lake
1DG 08 010	6	1964	2009	45	59.2	2.04	0.05	66 31	49 32	W	1800	500	776.8	Ice sheet outlet	Land
1DG 08 011	6	1964	2009	45	51.8	29.95	0.67	66 25	49 30	NW	1800	800	299.6	Ice sheet outlet	Land/lake
1DG 08 012/ 1DG 12 010	5	1973	2009	36	53.7	3.65	0.10	66 23	49 30	NW	1800	830	656.1	Ice sheet outlet	Land

1DG 12 014	6	1964	2009	45	55.3	1.66	0.04	66 20	49 36	NW	1800	850	261.5	Ice sheet outlet	Land/lake
1DG 12 015/ 1DG 16 120	6	1964	2009	45	61.2	4.09	0.09	66 18	49 39	NW	1800		277.4	Ice sheet outlet	Land/lake
1DG 16 142	7	1890	2009	119	96.1	-1.49	-0.01	66 07	49 54	NW	1800	800	316.7	Ice sheet outlet	Land
1DG 16 156	5	1964	2007	43	60.2	2.75	0.06	66 05	50 01	NW	1800	700	292.8	Ice sheet outlet	Land
1DG 16 167 a	3	1890	2001	111	5.0	-20.60	-0.19	66 09	50 12	E	1300	700	10.0	Ice cap outlet	Land
1DG 16 167 b	3	1890	2001	111	4.2	-17.09	-0.15	67 09	51 12	E	1300	700	10.0	Ice cap outlet	Tidewater
1DG 16 169	2	1987	2001	14	6.6	0.35	0.03	66 10	50 16	NE	1450	700	8.7	Ice cap outlet	Tidewater
1DG 16 171b	2	1987	2001	14	4.9	0.47	0.03	66 11	50 21	NE	1450	700	13.8	Ice cap outlet	Tidewater
1DG 16 171a	2	1987	2001	14	4.6	-0.01	0.00	67 11	51 21	NE	1450	700	13.8	Ice cap outlet	Tidewater
1DG 16 234	3	1973	2001	28	55.8	-27.33	-0.98	66 01	49 58	NW	1800	860	331.8	Ice sheet outlet	Lake
1DG 16 235	4	1973	2007	34	58.6	-8.31	-0.24	65 57	50 03	NW	1800	880	527.4	Ice sheet outlet	Lake
1DG 16 245	4	1987	2009	22	11.7	2.12	0.10	66 05	50 48	N	2000	850	90.7	Ice cap outlet	Lake
1DG 16 246	7	1890	2009	119	10.5	-17.75	-0.15	66 07	50 57	N	2000	750	54.4	Ice cap outlet	Land
1DG 16 250	5	1890	2009	119	9.2	-11.89	-0.10	66 16	51 25	E	1600	1050	12.4	Ice cap outlet	Land
1DG 16 256	6	1890	2009	119	13.1	-5.28	-0.04	66 18	51 35	NE	1800	700	128.6	Ice cap outlet	Land
1DG 16 265	7	1890	2009	119	27.9	-6.59	-0.06	66 21	51 48	N	1700	800	168.3	Ice cap outlet	Land
1DG 18 001/	5	1890	2001	111	22.1	-4.43	-0.04	66 24	51 57	N	1150	1000	3.7	Ice cap outlet	Land
1DG 18 003	2	1987	2001	14	11.5	-0.57	-0.04	66 22	52 07	E	1600	850	30.8	Ice cap outlet	Land
1DG 18 008	4	1890	2001	111	9.5	-4.95	-0.04	66 23	52 09	NE	1600	750	13.4	Ice cap outlet	Land
1DG 18 010	3	1973	2001	28	7.6	-1.25	-0.04	66 23	51 15	N	1600	700	12.6	Ice cap outlet	Land
1DG 18 013	3	1973	2001	28	6.4	-2.34	-0.08	66 23	52 20	N	1600	900	3.4	Ice cap outlet	Land
1DG 19 002	3	1992	2009	17	7.9	-1.80	-0.11	66 22	52 23	NW	1600	500	8.7	Ice cap outlet	Land
1DG 20 002	3	1890	2001	111	5.9	-23.54	-0.21	66 20	52 23	W	1600	800	7.7	Ice cap outlet	Land
1DG 20 007	7	1890	2009	119	8.3	-14.70	-0.12	66 17	52 24	N	1600	700	49.5	Ice cap outlet	Tidewater/land
1DG 21 011	6	1964	2009	45	7.7	-2.60	-0.06	66 15	52 35	NW	1700	150	31.3	Ice cap outlet	Land
1DG 21 014	3	1964	2001	37	19.5	-2.16	-0.06	66 15	52 39	N	1760	200	13.7	Ice cap outlet	Land
1DG 22 007	4	1985	2009	24	9.9	-2.42	-0.10	66 11	52 41	N	1760	100	25.9	Ice cap outlet	Land
1DG 23 003	2	1992	2001	9	2.7	-1.72	-0.19	66 12	52 48	NW	1450	1350	1.3	Ice cap outlet	Land
1DG 23 006	4	1890	2001	111	6.6	-13.78	-0.12	66 11	52 49	NW	1400	750	3.0	Ice cap outlet	Land
1DG 23 007	2	2001	2009	8	6.6	-0.54	-0.07	66 10	52 49	N	1400	250	6.7	Ice cap outlet	Land
1DG 24 002	4	1890	2001	111	8.4	-37.83	-0.34	66 09	52 52	W	1400	900	11.5	Ice cap outlet	Land
1DG 25 006	4	1890	2009	119	8.7	-19.28	-0.16	66 07	53 03	NE	900	700	1.4	Ice cap outlet	Land
1DG 26 001	1	2001	2001	0	3.7	0.00		66 08	53 05	NW	1000	250	1.5	Ice cap outlet	Land
1EA 05 003	3	1890	2001	111	2.7	-15.60	-0.14	66 21	53 02	W	1200	600	1.2	Mountain/valley	Land
1EA 05 004	3	1890	2001	111	1.9	-14.46	-0.13	66 20	53 04	NW	1000	700	1.3	Mountain/valley	Land
1EB 07 004	2	1992	2001	9	3.2	-2.32	-0.26	66 29	52 45	N	1600	650	5.4	Mountain/valley	Land
1EB 08 001	4	1964	2001	37	3.5	-16.41	-0.44	66 30	52 50	NW	1200	300	3.6	Mountain/valley	Land
1EB 08 002	3	1985	2001	16	2.3	2.10	0.13	66 30	52 51	N	1000	300	1.5	Mountain/valley	Land
1EB 09 008	3	1985	2001	16	2.7	3.02	0.19	66 27	52 53	NW	1050	300	1.1	Mountain/valley	Land
1EB 09 009	4	1964	2001	37	4.8	-5.88	-0.16	66 29	52 27	N	1700	600	3.8	Mountain/valley	Land
1EB 10 022	3	1890	2001	111	5.4	-11.74	-0.11	66 25	52 40	W	1100	1000	1.0	Mountain/valley	Land
1EB 10 025	3	1890	2001	111	6.7	-35.29	-0.32	66 23	52 44	NE	1500	800	10.8	Mountain/valley	Land
1EB 10 037	3	1890	2001	111	5.6	-24.49	-0.22	66 21	52 52	NW	1400	850	4.7	Mountain/valley	Land
1EB 10 039	5	1890	2001	111	4.2	-10.61	-0.10	66 21	52 55	N	1400	1000	4.1	Mountain/valley	Land
1EB 10 042	1	2001	2001	0	1.8	0.00		66 22	52 57	N	1300	550	1.0	Mountain/valley	Land
1EB 10 052	2	1985	2001	16	4.9	1.00	0.06	66 26	53 12	N	1400	650	5.3	Mountain/valley	Land
1EF 15 002	5	1985	2009	24	54.6	1.56	0.06	67 20	49 47	W	1800	500	1565.7	Ice sheet outlet	Land
1EF 16 001	4	1987	2009	22	65.5	0.85	0.04	67 11	50 13	W	1800	100	1501.3	Ice sheet outlet	Land
1FA 22 001	4	1985	2009	24	62.7	-4.84	-0.20	67 31	49 55	W	1800	150	1225.7	Ice sheet outlet	Land
1FA 23 001 a	6	1973	2009	36	52.6	4.61	0.13	67 28	49 44	W	1800	400	820.7	Ice sheet outlet	Land
1FA 23 001 b	6	1973	2009	36	53.4	3.24	0.09	67 28	49 44	W	1800	400	820.7	Ice sheet outlet	Land
1FA 23 001 c	4	1973	2009	36	52.8	15.11	0.42	67 28	49 44	W	1800	400	820.7	Ice sheet outlet	Land
1FA 23 002	5	1985	2009	24	53.6	1.13	0.05	67 25	49 42	W	1800	500	799.0	Ice sheet outlet	Land

Table B3: Summary statistics and characteristics of all ice sheet outlets, ice cap outlets and mountain/valley glaciers mapped in the southwest study area. Data on aspect, elevation, area, latitude and longitude taken from Weidick *et al.* (1992).

Margin ID	Number of years of data	Earliest year	Most recent year	Range (years)	Original length (km)	Margin width (km)	Total length change (% of original) Centre	Rate of change (% per year) Centre	Aspect	Primary classification	Terminus environment
1CH 02	4	1987	2009	22	50.0	34.4	0.00	0.00	SW	Ice sheet margin	Land
1CH 02/13	3	1987	2007	20	50.0	26.5	0.00	0.00	W	Ice sheet margin	Land
1CH 17	4	1890	2009	119	50.0	24.5	0.01	0.00	W	Ice sheet margin	Land
1CH 22	4	1890	2009	119	50.0	8.1	-0.01	0.00	SW	Ice sheet margin	Land
1CH 23	4	1890	2009	119	50.0	13.8	-0.03	0.00	NW	Ice sheet margin	Land
1DB 11 a	3	1987	2007	20	4.0	15.6	-0.02	0.00	S	Ice cap margin	Land
1DB 11 b	2	2001	2007	6	0.8	9.9	-0.01	0.00	S	Ice cap margin	Land
1DB 11 c	3	1987	2007	20	1.1	2.3	0.00	0.00	S	Ice cap margin	Land
1DB 11 d	3	1987	2007	20	2.2	2.1	-0.02	0.00	S	Ice cap margin	Land
1DB 13	4	1987	2009	22	50.0	16.9	0.00	0.00	W	Ice sheet margin	Land
1DG 03	5	1973	2009	36	50.0	11.5	0.00	0.00	SE	Ice sheet margin	Land
1DG 16 a	4	1890	2007	117	50.0	16.4	0.01	0.00	W	Ice sheet margin	Land
1DG 16 b	4	1973	2007	34	6.0	22.4	-0.01	0.00	SW	Ice cap margin	Land
1DG 16 c	5	1973	2009	36	12.3	24.5	-0.01	0.00	NE	Ice cap margin	Land
1EF 15 a	4	1987	2009	22	50.0	11.3	0.00	0.00	W	Ice sheet margin	Land
1EF 15 b	3	1987	2009	22	50.0	14.6	0.00	0.00	W	Ice sheet margin	Land
1FA 23/22	6	1890	2009	119	50.0	10.5	0.00	0.00	SW	Ice sheet margin	Land

Table B4: Summary statistics and characteristics of all ice sheet margins and ice cap margins mapped in the southwest study area.